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One of the goals of the Puget Sound Water Quality Action Team is communicating research results related to the Puget Sound environment and the management of the Sound's resources. The **1998 Puget Sound Research Conference** follows its three predecessor conferences (1988, 1991, and 1995) as the Action Team's largest and most visible effort to meet this goal.

Presented by the Puget Sound Water Quality Action Team and co-sponsored by state and federal agencies, local governments, universities and businesses, the fourth Puget Sound Research Conference was held on March 12 and 13, 1998 at the Washington State Convention and Trade Center in Seattle, Washington. More than 600 attendees – including scientists from government agencies, universities and consulting firms; resource managers; other decision-makers; students and members of the public – shared information on recent research findings and discussed the implications for managing Puget Sound and its resources.

These conference proceedings provide full papers for most of the oral presentations, abstracts of the remaining oral presentations and posters, and transcripts of the conference keynote session on "The Endangered Species Act and Related Natural Resource Issues", an evening session on "Communicating Environmental Science," and the conference wrap-up session. In addition, transcripts of question and answer periods at the end of the many of the conference's concurrent sessions are also included.

The papers presented in these proceedings have not been peer-reviewed, and the graphics and references in these papers are presented much as they were submitted originally by the authors. Limited editing was done for grammar and spelling.

We encourage you to contact the authors/presenters for further information and updates on any of the material presented in the proceedings.

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PUGET SOUND RESEARCH '98

KEYNOTE SESSION

Session Chair:

Duane Fagergren
Puget Sound Water Quality Action Team

Keynote Session – The Endangered Species Act and Related Natural Resource Issues

Welcome to Conference and Introduction

Duane Fagergren
Deputy Director, Puget Sound Water Quality Action Team

What do we hope to accomplish with this conference?

- We want to inform managers that are making very critical decisions right now on a whole host of issues we're working on.
- We want to inform citizens and help all of us understand what the basis of scientific knowledge is about the natural resources, and how we can protect them better.
- We want to share scientific information among researchers – from students to tribal members who are doing research in watersheds to local governments. It's the whole mix of agencies and academics that makes our understanding of Puget Sound much, much richer and broader, and this is one conference that brings all of you together.

We also hope that the conference can help us identify emerging issues, and I think our first panel this morning is going to identify what one of those big emerging issues is now, one that we've all been hearing about on the news recently: the proposed Endangered Species Act listing of salmon stocks in Puget Sound.

I urge all of you to participate in the conference by asking questions and staying focused. It's going to be a pretty intense two days, running well into the evening tonight. To get your time and money's worth and for us to understand all of the issues that are on your mind, we encourage not only your questions during the sessions, but also cornering people in the hall or talking over meals, and then staying connected after the conference. I think we all appreciate that a lot of the real value in a conference is meeting the person that's doing parallel research to yours but that you've never met before, or talking to a newspaper reporter about how we can explain the scientific understanding better.

Let me introduce our moderator for this morning's keynote panel, Bob Edwards, who is a City Councilman in Renton and also on our Puget Sound Council. I think Bob is the exact right person to talk, in an initial way, about what the Endangered Species Act (ESA) means to him as a local official and to introduce the rest of the panel. So with that, Bob, I'll turn it over to you.

A Local Perspective on Puget Sound Salmon Endangered Species Act Listings

Bob Edwards
Renton City Council and Puget Sound Council

Thank you, Duane. I'm not sure about beting "the exact right person" or any of the rest of it, but thank you for the kind words. I do serve on the Puget Sound Council, which advises the Action Team on policy issues, and also on the Renton City Council. I'm also a member of the board of the Association of Washington Cities as the immediate past president, so I communicate with other city council members and mayors from around the state.

We've dealt with many problems in Puget Sound over the last decade, but the approach has been largely voluntary, and that certainly fits with a lot of what we in local government believe and strive for. We tend to resist and have an aversion to mandates. And certainly the Endangered Species Act (ESA) is something that has more of a look and feel of a mandate. The ESA brings a stronger presence and a need to be accountable for salmon stocks in the Puget Sound basin. Local

governments know that the threat is real and that it will be costly. We do want to respond, but there is a lack of detail right now and that causes concern.

I was just back at the National League of Cities where a group of elected city officials from Washington State met with our congressional delegation. In the meetings that we had with both our Senators and, the one I attended, our Representatives, one of the top subjects that came up was the ESA and the listing of the Puget Sound Chinook salmon. There is great deal of fear and trepidation, I think, among elected officials. Partly, it's caused by the fact that we feel like there needs to be a road map for how we're going to get from where we are to where we need to be and no one has a lot of confidence that there is that road map.

The types of questions that have come up are: How high will the bar be for restoration and habitat protection, considering what we've been doing for a decade? How much counts for meaningful restoration and for a habitat conservation plan? The question that often comes up is, "Do we get credit for what we've already done?" Unfortunately, I think everybody knows that that's not quite the way it's going to work.

We're honored to have a panel today of distinguished leaders from the federal agencies that have major responsibility for implementing the Endangered Species Act and the Federal Clean Water Act. We have with us Will Stelle, the Regional Administrator for the Northwest Regional Offices of the National Marine Fisheries Service, and also the EPA's Region 10 Administrator, Chuck Clarke, who also serves on the Puget Sound Action Team. We have with us Robin Waples of the National Marine Fisheries Service who is the father of ESU's—evolutionarily significant units—and who will also explain the status of Puget Sound salmon stocks and how far we have to go to build back these critical runs.

After we hear from our panel members, we want to open this up for questions. This is how we're really going to be able to share information. So I'd like you to please help me welcome the esteemed panel, beginning with Will Stelle, followed by Chuck Clarke, and then Robin Waples.

Salmon Habitat–The Endangered Species Act and Some Points of Intersection with the Clean Water Act

Will Stelle

Regional Administrator, Northwest Regional Office, National Marine Fisheries Service

Thank you, and I'd like to thank Nancy, Duane, and the organizers for the invitation to appear here before you this morning. What I'd like to try to do this morning is three things, which is always ambitious. The first one of which is to simply describe to you the basic mechanics of the federal Endangered Species Act. The second is to describe to you our approach to the issue of habitat and how do we analyze whether habitat is good habitat or not. And the third is to discuss a little bit of the potential points of intersection between the federal ESA and the federal Clean Water Act (CWA).

We have described evolutionarily significant units (ESU's)—clusters of salmon runs—which either have been listed or are proposed for listing or are candidates for listing under the ESA. I won't go into the details here but to offer the following basic point. These ESU's cover a huge geographic area. This is the Western United States, and probably by the end of next year when we complete our chinook reviews, there is a pretty good likelihood that we will have final salmon runs listed under the ESA from the border of British Columbia down to Los Angeles. The geographic scope of this challenge is probably one of the most salient features of it. Don't' forget this map.

First, the basics of the ESA. In Section 4 of the ESA are the authorities for listing and rulemaking under the act. Once species are listed, then the obligations to conserve under the ESA kick in. Those obligations are contained in Section 7 of the Act, which describes what federal responsibilities are. There are obligations, described in Section 9 of the Act, which tell everybody not to "take" endangered species. There is authority to permit activities under Section 10 of the Act. Finally, I will go over areas of overlap with the Clean Water Act and the benefits of trying to pull those two statutes together.

First of all, the listing process. You've probably seen a lot of this in the news. It's a fairly orderly and routine and sophisticated process. Step one is to identify the proper clustering of neighboring salmon runs based on the concept of ESU's, evolutionarily significant units. Dr. Waples, on the panel here, was the principal author of that and I suspect he'll spend a little time this morning discussing its details.

Once we identify what the proper listing units are, we have to assess the risks that an ESU may be at risk of extinction now or in the foreseeable future based on abundance, trends and genetics of the populations within that ESU. Then we assess the extent of state or local conservation efforts to reduce those risks. We are obliged under the law to use the best available science in making these judgments. We share our technical assessments with state and tribal co-managers as we complete them.

Once a species is listed, Section 4 confers upon the agencies the rulemaking authority to apply "take" prohibitions to endangered and threatened species and to promulgate such other rules as may be necessary and advisable for the conservation of these listed species. The point I raise here is that this authority to promulgate rules is very broad and very flexible. Whatever rules are necessary and advisable. There's not a lot of guidance there.

OK, let's assume we have listed species. Let's assume that they are listed as threatened under the ESA. What happens? First of all, the protective obligations of Section 7 kick in for federal agencies. The scope of that obligation is that it applies to all federal actions including licensing, permitting approvals, funding, as well as managing federal assets such as federal lands and federal hydropower projects. So it's not just what the feds own, it's also what they permit and license. The substance of that obligation is that the federal agencies are to exercise all of their authority in furtherance in the purpose of the ESA, and the purpose of the ESA is to eliminate the risks that may cause species to go extinct. Suddenly that obligation to conserve species is an enforceable obligation against all federal agencies. This is a very, very powerful obligation.

There is a strict prohibition upon any federal action that may jeopardize the continued existence of listed species or modify their critical habitat. The procedure by which you determine whether a federal action may be jeopardizing, or whether or not you're properly exercising your authorities to conserve, is consultation with us at the National Marine Fisheries Service or with the Fish and Wildlife Service. They have biological expertise under the ESA to determine what those species need and to determine whether a proposed action is OK or not. If it's not OK, what terms and conditions, what changes they must be made in the proposal in order to minimize risks to the species? The recommendations that we make on how to change federal actions are very nearly binding on the federal agencies. So the Section 7 consultation process by which we advise federal agencies on how to change the way they normally do business is a very powerful tool: the most powerful tool of the ESA.

The prohibitions against jeopardy apply to federal land mangers in fresh water habitat, federal dam operators, like the Corps of Engineers and the Bureau of Reclamation. Permitting licensing and funding activities of for instance, the federal Energy Regulatory Commission, the Environmental Protection Agency, the Corps of Engineers, the Natural Resources Conservation Service, the Department of Defense, the Federal Emergency Management Agency, and the Department of Energy, to name a few. Again, this is just to give you the flavor of the scope of the obligations.

There are conservation obligations under the ESA that apply to non-federal agencies as well. They apply to all public and private activities: what you and I do. The substance of the obligation is that the ESA prohibits any actions that result in "take" of endangered or threatened species, unless those actions are exempted by incidental take permits, or special 4040 rule, which I described earlier on. "Take" is defined to encompass the activities that cause death, harm, harassment, or significant habitat modification that are highly likely to result in harm. The procedure by which these take prohibitions apply is automatic, which is to say they apply to you automatically. We don't have any specific consultation or advisory roles to describe to you what you can and can't do. Activities that constitute take are subject to civil and criminal penalties under the ESA.

As applied in the context of salmon, these take prohibitions may apply to dam operations which kill fish, freshwater habitat activities including forestry, agriculture, irrigation and water resource management, fishing, and hatcheries. Let me emphasize, though, that this take prohibition requires a high standard of proof. It's not just any old modification of habitat. One needs to prove that there was substantial habitat modification, so substantial that it did or will result in killing fish or altering their behavior. This is not an easy thing to prove. It's a hard thing to prove. But it's also a very powerful prohibition.

The ESA under Section 10 also authorizes us to permit take pursuant to habitat conservation plans whereby an entity may propose a long term set of activities, say land management activities, which we believe will improve conditions for salmonids and will provide support for their continued existence on that habitat. We, in turn, can approve those plans, and that approval carries some insulation from potential take liabilities under the Act. The scope of habitat conservation plans can embrace any activity or group of activities that may result in the taking of listed species. The obligations of these habitat conservation plans are to minimize and mitigate take to the maximum extent practicable, and to contribute to the long-term survival of species within the proposed activity.

The duration of typical plans that we have been working on over the past one to five years, largely with the large industrial landowners here in the Pacific Northwest, range from 50 to 75 years. They tend to be multi-species, they are not just for salmonids. They tend to cover all species that are or may be listed under the federal ESA, both aquatic and terrestrial.

These plans result in stability for the entity that has received approval. That entity, be it a land owner or a county, so long as they are implementing the plan as approved, will not be subject to further take prohibitions. They will not be subject to lawsuits, and if they are, that the U.S. government will defend with them against those lawsuits. These habitat conservation plans are a very, very important tool.

Now let me turn to the second topic I wanted to raise to you today which is, how do we think about habitat? Our fundamental objective under the ESA as it relates to Pacific salmon and the habitat of Pacific salmon is to seek properly functioning habitat conditions to support salmon populations. When we look at an action to determine what its effect will be on habitat, we identify whether that action is likely to impair properly functioning habitat, further damage impaired habitat, or retard the progress of that habitat. Again, their reference point here is properly functioning habitat. Properly functioning conditions (PFC) are defined, are to consist of sustained natural processes, not static characteristics. PFC is attained when a watershed's habitat forming processes (i.e. riparian communities, succession, bedload transport, run off patterns) function to maintain a healthy aquatic ecosystem over time. PFC is necessary for the long-term survival of Pacific salmon.

Now here are some of the ways in which we evaluate or assess PFC. We have what we call pathways and indicators. The pathway, and this is again by way of an example, the pathways are water quality, habitat access, habitat elements, channel conditions and dynamics, flow and hydrology, and upper watershed condition. Indicators, then, are at a higher level of specificity. Things that may affect that pathway of water quality include temperature, sediment, turbidity, chemical contamination, etc. Those things that traditionally encompass water quality concepts under the federal CWA. I'm not going to go through this list overall, but it'll give you a feel for it.

Again, in assessing whether or not those pathways will be achieved or are going to be provided for, we try to develop ranges of those individual indicators, whether or not it's properly functioning, at risk, or non-properly functioning. And again, this is intended to give you an example of how we evaluate whether or not a particular stream or a particular habitat segment is healthy, is properly functioning or not. And if not, why not and to what extent?

Going to my third point, our major thesis is that federal and state ESA and clean water agencies should marry their respective programs to conserve the aquatic habitat for ESA listed salmon, and to meet sate and tribal water quality standards. To coin a phrase, this should be killing more than one

bird with one stone. One-stop shopping. The objectives of ESA and Clean Water Act integration: effectiveness of achieving program goals, either aquatic health or water quality; state and federal efficiencies (one-stop shopping for the public); and flexibility in compliance at the watershed scale. Most of these are fairly self-evident.

The major points of overlap of the CWA and the ESA: First of all, they have the same purposes as applied to aquatic systems and Pacific salmon. The purpose of the CWA is to protect the physical, biological and chemical integrity of the nation's surface waters. The purpose of the ESA as it applies to Pacific salmon is to conserve Pacific salmon and the ecosystems upon which they depend. If you're a fish, the concept of water quality under the CWA and the concept of a healthy aquatic system under the ESA are the same thing. And if they're not the same thing, something is wrong. There is a geographic overlap. Here in the states of Washington, Oregon, California, and Idaho we have major con-compliance problems with the federal CWA, which Chuck will describe to you, and they are largely coterminous geographically with the ESA salmon listings. There is a technical overlap in water quality and aquatic health concepts and parameters. There should, and can, be overlaps in the regulatory machinery. The key issues in achieving this integration are to align the ESA and CWA objectives and to align the technical parameters for achieving those objectives, what I have described here as PFC.

Now, finally the practical constraints in doing this: time, money, and people at federal and state regulatory agencies. We're all badly overworked, and this is just one more item that will land on our collective plates. Variable state commitments at the DEQ levels. The state departments of Ecology or Environmental Protection are the principal focus for responsibility for complying with the federal CWA. These are delegated programs. So if the state agencies are not prepared to play, it will not work.

Thus far I had been mightily impressed in how uninterested the regulated community is in putting these two regulatory regimes together. I'm not quite sure why, but, again from my perspective, one-stop shopping makes a lot of sense. And then there's general inertia and risk-averse cultures in all of our various venues. Change is hard. Change requires a lot of effort on the part of all, and it doesn't come simply. We have traditional ways of doing business in the federal and state agencies. Permitees have traditional ways of doing business. Lawyers have traditional ways of doing business. And we will need to change those traditions if we are going to achieve the objective of marrying both the CWA and the ESA compliance here in the Pacific Northwest. With that, I'd like to stop, and again, I thank you for the opportunity to talk to you here this morning and look forward to your questions.

The Clean Water Act Now and into the Future

Chuck Clarke

Regional Administrator, Region 10, U.S. Environmental Protection Agency

Thanks, Will. I will try to do this rapidly to try and leave you some time for questions. I apologize for my voice. It's fading. I've been fighting a bug for the last three or four days and I think it's finally starting to win. I will try to get through this without losing my voice.

I'd like to start with a context piece. If we look at Will's charts of ESU's that are listed or proposed for listing under the ESA overlain with the streams and rivers in Idaho, Oregon, and Washington that currently do not meet water quality standards, you will note a lot of consistency between the ESA problems being experienced throughout Washington, Oregon, and Idaho and stream-water-quality conditions that have created some of those problems.

With this as background, I'm going to talk about two things today: (1) where are we today related to the Clean Water Act (CWA), and (2) where we need to go tomorrow to deal with some of the issues we face.

In many ways, when Will got up here and talked to you about the ESA, it reminded me a lot, after having worked at the state level for a long time, about the corrections debate that goes on within

the states. The way that people have dealt with corrections issues, criminal issues, over the last five or six or seven years is to build a lot more prisons. It is a mechanism that looks at the back end of the problem, not the front end of the problem.

ESA in many ways is very similar. If we haven't done a good job at water quality standards and we haven't done a good job at managing and making decisions related to the environment, we end up being subjected to the ESA. It is a reactive, at best, approach to dealing with it. It is an approach that, in many ways, will never allow us to go back and attain what we've lost historically because of the actions we've taken. As in many instances, you're trying to do through ESA the best job that you can, by not losing any more, and maybe gaining a little bit back where you can. I think it shows that, although we've made a lot of success in clean water in this country over the last 25 years, we have not made enough, and we need to look at doing things in a different way than we have in the past.

The CWA debate is shifting after 25 years. It's shifting from what was the debate in the 1970's over technology-based standards vs. ambient standards. We chose, in this country, to go to technology-based standards because we couldn't figure out how to deal with ambient standards because there was too much science involved. We didn't understand it very well, and so we said let's just look at the end of the pipe, and let's look at sources and tell people what they can discharge, and that will be an easier way of dealing with clean water. Now we're saying, gee, we made some progress, but it wasn't enough. And we have to look at the ambient conditions of the environment and decide how best we need to deal with water quality.

We're moving from point sources to nonpoint sources. The marginal costs of continuing to ramp down on point sources are getting higher and higher and higher. We have achieved a lot of successes. There still is some room for some additional gains, but the big gains before us are dealing with nonpoint-source pollution, and that means that we must move away from the kind of point-source orientation of industries and municipalities to dealing with agriculture and silviculture and a lot of the things that we all do as private citizens in the way we live, where we live, where development occurs, how we manage our transportation, how we deal with pesticides, how we deal with fertilizers, how we deal with all those issues that contribute to nonpoint source problems. We're fundamentally at that crux right now of trying to move off of the traditional approaches in the dealing with the nonpoint sources. It is an extremely difficult issue for regulatory agencies.

People in this country believe that they are environmentalists. If you do polling, 80 percent of the people in the country believe they are environmentalists. If you ask them questions about what they want to do to protect the environment, they say go out and enforce against municipalities and industries, and by god, we're behind you 100 percent. But if we say, "Well, how about if you do something," their will power rapidly declines. If you look at some of the national polling data, when they started looking at wetlands issues as a definition of a commitment to the environment, people started becoming much more interested in their personal property rights than they did in the environment. When we asked the questions about going out and hammering on an industry, they got real excited again. So I think it is going to be a difficult issue over the next decade in trying to figure out how to deal with nonpoint issues because they are not easy to define.

There are a number of legal decisions that have occurred over the last few years that are putting some pressure on the CWA to change the way it does business.

The first issue relates to water quality standards. Let me give you a very simplified version of how the legal issues of water quality standards are changing. The EPA in this region is involved in four states: Washington, Oregon, Idaho, and Alaska. We have now lost lawsuits in four states—Washington, Oregon, Idaho, and Alaska—on how we have managed the CWA, and more specifically water quality standards, over the last 15 years. We have been put in a position of having to redefine how states address their water quality standards, and how they bring water body segments that don't meet water quality standards back into compliance with the standards.

Every two years the states take all the water quality data that they have on all their stream

segments in their state and make determinations of what waters meet or do not meet water quality standards. As a result of this work they publish the 303(d) list. This is a list of all water body segments in the state that don't meet water quality standards. After that list is compiled, the states have to develop a strategy for every one of those segments on how to bring it back into compliance with the water quality standards.

Because of the court cases that the EPA has lost in the Pacific Northwest, the EPA is now on the hook to make sure that states develop and implement the strategies for bringing waters back into compliance with water quality standards. If the water bodies don't come back into compliance after the states have tried to implement their strategies, then you have to go back into that segment again and develop new strategies to try to bring that segment back into compliance.

This is a much different approach than was happening five years ago, ten years ago, or fifteen years ago. Will made the statement that he's not sure exactly why people haven't been as interested in merging the ESA and the CWA as we thought they would be. In many ways the TMDL (Total Maximum Daily Load) and the 303(d) List (those water body segments not meeting water quality standards) are about three to four to five years behind the ESA in the sense of people recognizing the potential impacts on them in the community. There is not a choice on coming into compliance. It is being mandated by the courts. So as we follow along behind the ESA, and as we recognize the issues, we're trying to figure out a way to merge strategies and actions to address CWA and ESA concerns.

A second issue: Section 401 water quality certifications. A state has to certify that actions are consistent with the CWA. This is called a 401 Water Quality Certification. We are now starting to get some court decisions that say that nonpoint source actions, which we traditionally had not looked at under 401 certifications, have to be consistent with water quality standards. The first big case that came up in the Oregon courts dealt with grazing on federal lands, and the court decided that grazing was subject to CWA water quality certification. So all those private farmers who had received grazing permits for the last 100 years, under the federal law now have to go to the state of Oregon and get a water quality certification for every one of those permits. It doesn't take a rocket scientist to figure out that if grazing may be subject to that, why isn't road building in forest lands, and why aren't other activities going to be subject to water quality certifications.

A third issue: the water quality, water quantity linkage. There has been, in the West, a real desire to keep these issues separated for the last 150 years. First in time, first in right: I got my water and nobody can ever change the fact that I get that quantity. But the Supreme Court issued a decision about five years ago, the Jefferson PUD decision, that said there is a specific linkage between quantity and quality. Some of the segments that we show as not meeting water quality standards are listed because they don't have sufficient flow to meet water quality standards. This is a fundamental shift, which will lead to a fundamental debate over water quantity policy in the West over the next decade.

Fourth issue: tribal trust responsibility. As an example, there's a decision in New Mexico where Albuquerque had gotten a permit for the discharge of their municipal treatment system. The tribe downstream sued the permitting agency saying that they have water quality standards on their reservation. The water being delivered at their border did not meet their water quality standards. The court found in favor of the tribe: that there is a trust responsibility to deliver water to the border that meets water quality standards. Again, a shift in policy on the way that's been handled nationally.

A final issue: the shift to binding obligations to protect listed species and their habitat when the ESA takes effect. The issue of ESA consultation goes beyond CWA for many agencies. I had a discussion with the City of Tacoma this week about a Superfund cleanup in Commencement Bay. When we discussed remedies, my first question was "Have you consulted with National Marine Fisheries Service under Section 7 – or Section 10 because there are private companies involved – on making a determination?" The answer was no, we haven't yet. The presence of the ESA changes not only the CWA but also other aspects of regulatory authority. This has created a number of difficulties related to trying to solve these issues. Will talked about some of them, but just in the sense of double

jeopardy, if you do a Habitat Conservation Plan (HCP), apparently, with either the Fish and Wildlife Service or the National Marine Fisheries Service, you typically get a letter that says, its nice that you've done that effort, but that doesn't necessarily mean you comply with the CWA. And we may come back in later and reexamine what you're doing to make sure that it is consistent with the CWA. We have double jeopardy in the system. That's why we're trying to push for one stop shopping and trying to figure out a way to merge activities to meet the requirements of both these federal laws.

A number of issues confront us as we try to address better merging of federal regulatory programs.

There is currently a lack of communications between agencies and levels of government. I think we need to figure out a way to deal not only with the relationship at the federal level, but the relationship between us and the states and us and the local jurisdictions. We're working hard on that, but there still is significant disconnect going on.

Agency resources are non-existent or mis-aligned. For traditional environmental agencies, you have an air program, a water program. It's all medium based, not geographic watershed based. The CWA and ESA approaches are geographic based. They look at ambient impacts in a watershed. They don't look at whether you have an air program or a water program, and we need to figure out how to re-align our resources.

There are also issues of risk acceptance. As Will mentioned, the HCPs that have been done are for 75 years. When we write NPDES permits, they're for five years. We at environmental agencies have been less willing to accept a long-term risk in making environmental decisions. We think we got burned on dam re-licensings when they went for 40 years, and we don't really want to get into that business again. So we're trying to merge how much risk we're willing to accept as we merge what's going on related to ESA and what's going on related to the CWA.

The final issue: developing science. I've been in three environmental agencies in the last six years and I've tried to get them to do "state of the environment" reports. I've said, "we've collected data for 25 or 50 years, monitoring data and so forth, and I want to use that now." In response, I've been told that QA/QC isn't very good and we're not sure we can forecast or project with that information what changes need to be made from a policy side. And so I've said, in every instance, "Well, that makes it easier for me because I've just found $10 million dollars worth of budget cuts for the next year." Because if you can't use the data, if you can't use the science, then why do the work in a social setting. I mean, I need good science to be able to support good policy decisions.

How do we deal with some of the issues raised by the shifting focus the CWA and the merging of CWA and ESA regulatory programs? Where do we need to go tomorrow? One solution is attention and focus. We're trying to get people's attention. Will and I have now given this talk probably five times in the last six months, where we're on the panel together trying to get people to take both of these seriously, and work together on both CWA and ESA, and I think we're trying to raise the attention and focus on it.

Secondly, we are still trying to settle some of the lawsuits that are out there. We're working on trying to get those done, and that's going to be critical to our long-term success.

Third, we need to try innovative approaches. We're currently working with all the interested parties on a timber, fish, and wildlife agreement in Washington. We're trying to negotiate both the CWA and the ESA requirements with the regulated industry, the environmental community, the tribes, and the state to see if we can't figure out a way to resolve the double jeopardy issue, at least in the state of Washington, on private forest lands. Whether we'll be successful or not, I don't know, but we're attempting to deal with that.

Fourth, we'll need to re-align resources. I think it goes without saying that we need to move to a more geographically based system. In our region we've set up a new ecosystem division that cuts across our entire organization to try to deal with underlying science and take action.

Finally, for those of you who have been paying attention, the President has announced a new

clean water agenda. We think it's extremely important to get this agenda through Congress because it has a significant amount of resources that will be provided to deal with nonpoint sources in this country. One of the reasons that we did a great job in the 1960's and 1970's to deal with municipal waste discharges was because the federal government paid for it. We can talk about all kinds of things, but it paid for it and it provided 90 percent of the money through grants. If we're going to deal with nonpoint sources, we better figure out a way to start dealing with the costs involved. I don't think we're going to get a lot of people voluntarily coming to the table and deciding that they just want to do better and spend the $100 thousand, or million, or two million, or three million necessary. The President's clean water agenda has about a half a billion dollars of new money to try to deal with these issues. I think it's critical that that becomes a portion of the solution over the next decade.

With that, thank you very much.

Evolutionarily Significant Units and Listing of Pacific Salmon under the Endangered Species Act

Robin Waples
Northwest Fisheries Science Center

For the last six years I've been part of a group at the Northwest Fisheries Science Center trying to answer a few questions about the status of Pacific salmon. The key questions we have to address are, first, "Do we have a species?" and, second, "Is it threatened or endangered?"

The first question, it turns out, is fairly complicated because of the language in the Endangered Species Act that allows listing not only of species or even sub-species, but also of distinct population segments of vertebrates, and that includes salmon. For salmon, where you have literally hundreds or thousands of local spawning populations for each of the biological species, this is a fairly significant issue.

Now what is a population that's distinct? There is a wide variety of ideas about that, so we had to develop a policy about how to implement that under the ESA. As Will said, our policy is based on a concept of evolutionarily significant units (ESU's). I'm not going to go into the details here because of the time, but we've taken a holistic approach where we try to integrate all biologically important information: genetics, life history, habitat information. We're trying to identify major chunks of diversity for the species as a whole that largely evolved independently of each other. Collectively they add up to a rough species as a whole. If we save those big chunks, then the species as a whole should be sustainable in the future.

In terms of the risk analysis, the second question, we look to the language in the Act where there are some definitions of what an endangered species is. We try to tie our risk analysis back to this language in the Act. And there is another twist. The Act says the listing determination has to be based on the best scientific information available after consideration of conservation measures. So at the center, in general, we stick to the technical information about the status of the stocks, and by mutual agreement, the conservation measures are generally evaluated at the regional level. So they're to ones that actually make the listing determinations.

There is a connection between the two major questions: What is an ESU and what is at risk of extinction? There are two kinds or errors we want to avoid in defining ESU's. First, we don't want to identify artificial units that are actually portions of the actual, underlying units. If we make this type of error we would be addressing a group of fish for which extinction is not going to mean much: what does it mean to lose part of one unit and part of another unit? If you lose a whole unit, you know what that means. Extinction is a biological process. It's irreversible. You can't get it back, but loss of portions of two related populations is difficult to interpret biologically or in terms of the ESA.

The other error we want to avoid is the arbitrary definition of a unit's geographic range based on political jurisdictions. Consider a population or group of populations that occur across an international boundary, say between the US and Canada. In spite of the international boundary and the fact that ESA listing sanctions would not necessarily apply outside the US, we think it's important, first, to identify a biologically meaningful unit, and then do the risk analysis on the whole unit. If we focus only on the U.S. part of population, you have the question "What does the extinction of that little bit mean?" It doesn't mean much unless you understand the dynamics in the relationship between that population to the rest of the populations in the real biological unit. This is a point on which we actually differ a bit with the Fish and Wildlife Service. They have used international boundaries as a way of defining distinct population segments.

I'll now go briefly through our status reviews. In 1994, we launched coast-wide status views for all the species of Pacific salmon and anadromous trout. We've done six of the seven now. I'll discuss five species: sockeye, coho, chum, chinook, and steelhead.

Sockeye salmon

The review of Puget Sound sockeye (pink) salmon was completed a couple years ago. Almost all of the pink salmon in this area are odd-year pink salmon, and for the most part those populations are healthy. There are a couple populations that are of concern, but for the most part, they are in really good shape. This ESU contains Strait of Georgia populations as well.

Sockeye salmon have a very unusual life history generally tied to juveniles rearing in a lake for one or two years. So what we have is a very, sort of, mosaic of population structure. They occur in discrete and isolated populations. For the most part, we have ESU's that are individual populations. This is very different from other species.

In our announcement two weeks ago, we have proposed to list as threatened Ozette Lake sockeye on the Olympic Peninsula. Baker River sockeye are identified as a candidate species. Basically, that means there's a lot of concern, but also generally a lot of uncertainty. Looking at the abundance of Baker River sockeye we note a really depressed state through the late 80's. If we did the stock assessment then, we probably would be proposing listing now. However, we've seen a huge spike in the abundance of Baker River sockeye in recent years. It's hard to know what to make of that. Is that going to persist, or are we going to back down in the troughs in the next few years? This large interannual variability in abundance is a concern. And also there's a lot of heavy human involvement in the perpetuation of that stock. It can't survive at the present time without human intervention. So that's another factor.

Coho salmon

A year or two ago the National Marine Fisheries Service announced that Puget Sound coho salmon would be a candidate species. There is plenty of reason for concern, but there are a lot of coho salmon in Puget Sound. There is a lot of uncertainty about how the Sound's coho are sustained by natural production.

One of the reasons for concern for Puget Sound coho, based on data pulled together by Laurie Weitkamp, who is head of our status review, is that the size of coho salmon caught in terminal fisheries in Puget Sound has declined by about 50% in the last twenty years. A lot of factors might contribute to this decline, but whatever the reasons, the fact that the fish are half as big as they were 20 years ago means that they are going to have fewer eggs, they will only be able to dig shallower redds that are more likely to be scoured by rains, and so on. We believe it is a significant risk factor we believe for the natural population.

Chum salmon

Much like the pink salmon, most of the chum salmon in Puget Sound are fall run, and they are

relatively healthy. Their ESU, again, extends up into the Strait of Georgia. A few isolated populations are of concern, but in general, they are very robust and near historical abundance. On the other hand, there is a very distinctive group of summer run chum salmon from Hood Canal. Genetic data indicate that this is a very ancient lineage. Very distinct from other populations and even distinct from the summer run in south Puget Sound. The Hood Canal summer-run chum are in really tough shape and we have proposed listing for them.

Looking at the data for Hood Canal chum salmon we see that the fall run is quite robust, although a lot of those are hatchery fish. Until the last few years, however, Hood Canal summer chum numbers have been very low. In the last couple of years there has been a big spike in numbers for some of the Hood Canal summer chum populations. A lot of the populations remain essentially zero or very few spawners, but some of them have made a huge comeback in the last couple of years. So, again, this is a very difficult ESU to evaluate,

Steelhead

A listing determination for Puget Sound steelhead was announced about a year or so ago. The population in Puget Sound was not really considered healthy but it was not considered to warrant listing at the present time.

Chinook salmon

As everyone knows, Puget Sound chinook salmon were proposed as a threatened species two weeks ago. I'd like to point out that all of the listing determinations, all of the proposals for Puget Sound stocks at the present time are just proposals. There will be year of public comment and review of new information before any final listing determination is made.

One of the reasons for concern for Puget Sound chinook salmon is a decline in productivity of the population. Looking at a combination of data for all runs in the Skagit River we see a steep decline in the number of recruits per spawner—a measure of the productivity of the population. The really scary thing is that this is happening in the face of declining harvest rates. Typically, one of the tools managers have to deal with declining recruits and declining populations is to ease off on the harvest rate. They've done that to a significant degree, but there has been no response in the populations.

Finally, before I close, since this is a science conference, I wanted to point out that there a lot of technical issues that are very difficult in both ESU and risk analysis determinations, and we continue to work to try to improve the process. For the risk analysis, you know the definitions of the threatened and endangered but basically we have to deal with questions like: What is likely to become endangered or threatened? What is the foreseeable future? What is a significant portion of an ESU? That's a major question. How do we evaluate the genetic and ecological effects of hatchery fish?

Questions and Answers (Keynote Panelists)

Clarke: [unrecorded question and beginning of answer] ... work out how best to deal with that. It's an issue, having run state agencies, and gone through water quality standards processes, and knowing how difficult they are and how political they can become, we know it is going to be a challenge at best. We're trying to figure out how to really get our act together so that we can provide information that is useful and usable for the standards process. But we are looking directly at that issue.

Stelle: Let me just add one example to give you a sense of what the options may be. If you recall the chart I put up with the pathway of water quality, and the indicators are temperature, turbidity, and sediment loading. Those are the conventional expressions of water quality under state and federal water quality criteria and standards. Let me describe two situations where you may be able to achieve those standards. Take a concrete pipe, or take a small stream and line it with concrete. Line the upper banks with concrete and pave it. Plant some vegetation over that stream; small bushes, not big trees, to deal with the issue of temperature. And you may have yourself a stream segment that satisfies state water quality standards. But from a fish perspective, it's a dead stream. That's really the difference between the conventional notion of water quality as applied and this more complicated concept of a healthy aquatic system. I boil it down to the two adjectives of sinuousity and complexity. Sinuousity and complexity should be the characteristics of a healthy aquatic system. We are not looking at paved channels.

Friedman-Thomas: Will, I was recently reading the federal register document on the proposed listing and I was interested in your presentation on the Section 10 types of activities that would be considered for considerations of "take," and you mentioned permitting, licensing, and funding. I remember reading in the proposed listing document about rulemaking, and I didn't hear you speak about that today. I wonder if you could talk a little bit about that and what the expectations are for both federal rule making as it pertains to potential listings and subsequent "take" considerations, as well as state level rulemaking.

Stelle: That was one of those finer points in the earlier slides that I raced through. Section 4 of the ESA authorized the agencies to apply take to threatened species. This gets technical. Technically under the statute, the prohibition against take automatically applies by statute to activities that harm endangered species. The services have the authority to apply that same prohibition to threatened species as well as endangered species. The Fish and Wildlife Service, as a general program regulation, promulgated a rule ten years ago that said every time we list a species as threatened, we will automatically apply "take," period. We have not done that under the National Marine Fisheries Service, and every time we promulgate, make a final decision on listing a species, we issue also a rule that applies take to it.

The interesting thing, from my perspective, is the ability to shape the way we apply or don't apply "take" to threatened species in order to accommodate commitments by states or counties in conservation plans to recover species or their habitat on that landscape. If we're able to get those firm, reliable conservation strategies in place, we can by rule, not apply "take" to those activities or that geography. There is a lot of flexibility in the way in which we can or cannot apply the prohibition on "taking" to activities that may harm a threatened species. But it's a complicated point.

Houghton: Will, there are a number of activities underway in the Sound, in particular, in Commencement Bay, on clean up of contaminated sediments under CERCLA and state sediment management actions. I wonder if you could comment a little bit on how ESA proposed listings at this point might effect those actions, and also in particular the schedules or the additional reviews that would be required for those proceedings.

Stelle: I'm not that familiar with the remedial work in Commencement Bay and elsewhere. As a general matter, the remedial work under CERCLA has two objectives to it. The first one of which is

to clean up for purposes of human health reducing risks to human health and the environment. The second is to remediate the site in order to remedy damages to natural resources caused by the hazardous substances. It's in that second phase of the fixing the damages to the natural resources where some of the principal natural resources that may have been damaged by those CERCLA sites may well be salmonids. I would hope that in the design of the remedial plan, that salmonid needs have been identified and been taken into account. If they haven't, we have a problem. In the second point of the question; what kind of additional reviews? The approval of those clean up plans is a federal action. They will require consultation under the ESA and it's just one more thing. Frankly, we have a serious problem of what I think of as bottlenecks. The workload here is enormous and the staffing that is available to do it is minimal, and the two do not meet.

Malmgren: Robin, a question regarding hatchery fish. In some of your slides, there was an indication of low populations in, say, 1927. I'm familiar with the problems of the four H's, and so forth, and I'm hoping that you will be developing very, very careful statistics on the impact of the hatchery fish. Many of the tribe's areas would be destitute without our hatcheries, and, my bias is habitat restoration, are you being very, very careful to evaluate the risk associated with hatcheries?

Waples: That's a good question. I guess the answer is we are as careful as we can be given limited data. Unfortunately, the possible effects of hatchery fish on natural populations are quite diverse and complicated, and in general, fairly easy to understand conceptually. Sure, these sorts of things can happen, and we have evidence that they have happened in certain cases. But in any particular example, for any particular population say of any particular species, it's very difficult, even with a fairly impressive monitoring program, really to know for sure what the effects have been. In general, we don't have very impressive monitoring systems. Sometimes we have almost no data whatsoever. So that is one the biggest sources of uncertainty and also controversy I think about some of the listing determinations is how you deal with the effects of hatchery fish. So I guess, again, our answer is, we are doing the best job we can in looking carefully at the data, but it's not easy, given the scarcity of the data.

Malmgren: I hope you're really careful because we in the state have a system of funding fish and wildlife by our fee structures and so forth. And if we don't have the fees and so forth we've got to really look at other monies to fund the system, and I'd hate to see the whole deck of cards and everything collapse. So I think what you're doing is extremely important for the total resource. Thank you.

Waples: There's no reason why hatcheries can't be consistent with the ESA. They can be in two ways. One, if they're part of a recovery plan for at risk populations. And second, if it's possible to keep the hatcheries as separate as possible so that the level of incidental take doesn't rise too high. Both of those are avenues.

Malmgren: I'd like to hear the hatcheries as part of the recovery plan.

Waples: It already is, in many of the ESU's that are listed.

Coachman: I work for NPDES MS4 Phase One, and we have lots of projects that are federally funded and federally permitted that are in the pipeline. And we're wondering how the Section 7A requirement for conferences will be affecting us. You haven't addressed that so far, Mr. Stelle.

Stelle: Good question. The Section 7 prohibitions on federal agencies jeopardizing the continued existence of listed fish apply basically to species which have been listed as a final matter under the ESA. For those that have been proposed for listing, there's also another tier of protection. And there is a process associated with that protection as well. The Section 7 of the Act says that, for proposed listings, if federal agencies are proposing to do things that may jeopardize, then they have to confer with the National Marine Fisheries Service to determine whether or not it will, and if it does, then they have to change it. That's the conferencing obligation, and it attaches to activities that may

jeopardize proposed listed species. I'm not quite sure what the precise question is, but the threshold for triggering a conferencing obligation is higher than it is for consultations. It's only those activities that may jeopardize, not which may effect. And I expect a small avalanche of requests, conferencing requests, over the next six months as federal agencies sift through what they may be doing and their potential impact on salmonids. Again, it's part of the workload problem.

Maria-Victoria Peeler: My question is for Will and Chuck both. I was wondering, Will, if you can address the prelisting agreement section in ESA and whether, under a prelisting agreement, if either the ESA or the state can make a jump start on this process.

Stelle: The short answer is yes. The reference is to authorities under Section 4, which stipulates that we can enter into agreements. They are like habitat conservation plans, they are conservation agreements with an entity, be it a federal entity, a state entity, a county or private entity, and those prelisting agreements basically get rolled over in the event of a listing as a habitat conservation plan. The basic deal is if you will promise to do X, Y, and Z over the next period of time and if you adhere to this promise, then we promise that you won't be subject to potential "take" liabilities of the ESA in the event species get listed. Those are prelisting agreements, and yes, they are available.

Peeler: So the second question to Chuck. Does EPA have in mind any plan to do something like this?

Clarke: That's part of the discussions that we have been having recently. I think, to give you a specific example where we might be able to really force-fit the two issues and do it the right way, that there have been a lot of questions, and I mentioned the 303(d) list and Total Maximum Daily Loads (TMDLs) that are going to have to be established across the region. In many ways, there have been questions about the implementation authority related to making sure that a TMDL to bring a segment back in compliance with the CWA is enforced. One of the ways that we may make sure it's enforced is make that a part of the ESA consultation process. That to avoid going forward, you not only have to do a TMDL, but you have to implement all the actions associated with the TMDL to meet both the requirements under the CWA and under ESA. And so trying to figure out a way to fit those two issues together takes you, in essence, back to Will's point of one-stop shopping. We're also talking right now, in many instances, about how to get out in front of other potential listings in the future, so that we can sit down and deal with states jointly on water quality standards and things like sediment and temperature and other aquatic issues, rather than waiting until those processes occur later on. So we are trying to figure out a way to deal with those.

Parr: I'm with the Washington Department of Fish and Wildlife. This question is directed to Robin Waples in terms of the genetic constitution you currently understand about the stocks at risk. Evolution is a dynamic process and my question is "Are future ESU's of the current ESU stock structures based on original genetic structure, and secondly what influence has habitat alteration had on the selective pressure or differential survival of salmonids in ESU range?"

Waples: Again, that's a good question. In general, in defining ESU's, what we're shooting for is to find ESU's or identifying units (usually groups of populations for most species except sockeye) that we believe behave largely independently from other large units over evolutionary time frames, which we would define as, say, hundreds or thousands of years. So what we're looking at in terms of ESU's are largely a result of a process of evolution over the last hundreds or thousands of years, say since the last ice age. We don't try to project which groups will be ESU's into the future. We think that if we identify these major chunks and conserve as many as possible, as you say, the process of evolution is dynamic, and it'll go on by itself. At some rate in the future, if we save enough of those, there will be enough options for the species as a whole to evolve, I think.

PUGET SOUND RESEARCH '98

PLENARY SESSION

COORDINATED RESEARCH AND MONITORING IN PUGET SOUND AND THE GEORGIA BASIN

Session Chair:

Scott Redman

Puget Sound Water Quality Action Team

The Puget Sound Ambient Monitoring Program

Scott Redman
Puget Sound Water Quality Action Team

Introduction to the PSAMP

The Puget Sound Ambient Monitoring Program (PSAMP) is a long-term, comprehensive program to assess the health of Puget Sound and its resources. Approximately 10 years ago, PSAMP was initiated to evaluate the effectiveness of the Puget Sound Water Quality Management Plan, to assess long-term trends in environmental quality, and to improve decision-making and prevent overlaps and duplication in monitoring efforts.

The PSAMP is implemented as coordinated studies by Washington State Departments of Ecology, Fish and Wildlife, Health, and Natural Resources, King County's Department of Natural Resources, and the U.S. Fish and Wildlife Service. The Puget Sound Water Quality Action Team coordinates the program with the assistance of representatives of the implementing agencies and the U.S. Environmental Protection Agency.

Through the studies that comprise the PSAMP, data on marine and fresh waters, fish, sediments, and shellfish in Puget Sound have been collected since 1989; surveys of nearshore habitat have been conducted since 1991; marine bird populations have been surveyed since 1992; and marine bird contamination has been studied since 1995.

PSAMP Findings Presented at Puget Sound Research '98

The results of PSAMP studies and the relevant work of other scientists are used to address five aspects of the health of Puget Sound: biological resources, physical environment, toxic contaminants, pathogens and nutrients, and human health threats. Results in each of these areas were presented at the 1998 Puget Sound Research Conference.

Biological Resources

PSAMP develops information about the state of Puget Sound's biological resources through a number of studies. PSAMP studies do not evaluate the condition of marine or anadromous fish resources or shellfish stocks. Results from PSAMP studies presented at Puget Sound Research '98 included the following:

Marine Birds

- Status and Trends for Selected Diving Duck Species Examined by the Marine Bird Component of PSAMP (Nysewander and Evenson)

Marine Mammals

- Disease Screening of Harbor Seals (*Phoca vitulina*) from Gertrude Island, Washington (Lambourn et al.)

Nearshore Vegetation

- Floating Kelp Resources in the Strait of Juan de Fuca and along the Pacific coast of Washington (Mumford et al.)
- Mapping Shorelines in Puget Sound II. Linking Biota with Physical Habitats (Dethier and Schoch)

Puget Sound Research '98

- Mapping Shorelines in Puget Sound III. Management Applications for Inventory and Monitoring (Berry et al.)
- Puget Sound Intertidal Habitat Inventory: Vegetation Mapping (Ritter and Bailey)

Benthic Macroinvertebrates

- The Distribution and Structure of Soft-bottom Macrobenthos in Puget Sound in Relation to Natural and Anthropogenic Factors (Llanso)
- Marine Benthic Invertebrate Communities near King County's Wastewater Outfalls (Laetz)

Physical Environment

PSAMP studies address the status of, and changes in, the Sound's physical environment, especially the Puget Sound shoreline and the physical character of Puget Sound's marine waters.

Shoreline

- Mapping Shorelines in Puget Sound I. A Spatially Nested Geophysical Shoreline Partitioning Model (Schoch and Dethier)
- Probability-based Estimation of Nearshore Habitat Characteristics (Berry et al.)
- Puget Sound Intertidal Habitat Inventory: Shoreline Characteristics Mapping (Bookheim and Berry)

Marine Water Physical Character

- "The Puget Sound Signal" in the public evening session on Local Effects of El Niño (Newton)
- Variations in Residence (Flushing) Time in the West Bay of Budd Inlet, 1992-1994 Hydrographic Studies (Albertson et al.)
- Assessing Sensitivity to Eutrophication Using PSAMP Long-term Monitoring data from the Puget Sound Region (Newton et al.)

Toxic Contaminants

A major focus of the PSAMP over the years has been on the distribution and effects of toxic contaminants in Puget Sound. PSAMP findings presented at the 1998 Puget Sound Research Conference include the following:

Sediments

- Toxicity of Sediments in Northern Puget Sound-A National Perspective (Long and Dzinbal)
- Response of the P450 RGS Bioassay to Extracts of Sediments Collected from Puget Sound, Washington (Anderson et al.)

Shellfish

- Trace Metal Contamination in Edible Clam Species from King County Beaches (Stark)

Fish

- Factors Affecting the Accumulation of Polychlorinated Biphenyls in Pacific Salmon (O'Neill et al.)
- Persistent Pollutants and Factors Affecting Their Accumulation in Rockfishes (*Sebastes* spp.) from Puget Sound Washington (West and O'Neill)
- Geographic and Temporal Patterns in Toxicopathic Liver Lesions in English Sole (*Pleuronectes vetulus*) from Puget Sound and Relationship with Contaminant Concentrations in Sediments and Fish Tissues (O'Neill et al.)

Marine Birds and Mammals

- Contaminant Monitoring of Surf Scoters near Tacoma, Washington (Mahaffy et al.)
- Elevated PCB Levels in Puget Sound Harbor Seals (*Phoca vitulina*) (Ross et al.)

Pathogens and Nutrients

PSAMP studies investigate water quality problems related to pathogens (as indicated by fecal contamination) and excess nutrient loadings. Results of PSAMP studies in these areas reported at the 1998 Puget Sound Research Conference include the following:

- Long-term Trends in Fecal Coliform Levels in Three South Puget Sound Bays and Links to Watershed Remedial Action (Determan)
- Variation in Primary Productivity of Budd Inlet (Newton et al.)
- Sources of Variability in Water Quality Monitoring Data (Edinger)

Human Health

The PSAMP investigates toxic contaminants, pathogens, and paralytic shellfish poisoning (PSP) toxins as human health threats in the Puget Sound environment. Results from studies of toxic contaminants and pathogens are listed above. One paper on PSAMP's monitoring of PSP was presented at this conference:

- Temporal and Spatial Distribution of PSP Toxin in Puget Sound (Determan)

PSAMP Reports

In addition to presenting results at Puget Sound research conferences and at other scientific meetings, the PSAMP communicates its findings through the following publications:

- Agency reports—as part of the participation in the PSAMP, member agencies all produce and disseminate technical reports on their PSAMP efforts. These reports are the primary publications of PSAMP findings.
- *Puget Sound Update*—the sixth Update (1998) has recently been completed. This report is intended to be accessible, yet comprehensive documentation of recent findings of the PSAMP. New editions of the Update will be produced every two years.
- *Puget Sound Notes*—an occasional, technical newsletter for Puget Sound scientists.
- *Sound Waves*—a bi-monthly or quarterly newsletter for citizens of the Puget Sound region. Since late 1996 this newsletter includes a page devoted to recent findings of the PSAMP on the health of Puget Sound.

Data developed from PSAMP studies are also available. Various electronic and hard copy formats are available via request to the principal investigator. Contact Puget Sound Water Quality Action Team staff for information about whom to contact for various data sets or visit the Action Team's Web site at http://www.wa.gov/puget_sound.

A Conceptual Model for Environmental Monitoring of a Marine System Developed for the Puget Sound Ambient Monitoring Program

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Introduction

Environmental monitoring programs are established to assess the status of ecosystem components with the goal that this information will be used to direct human management decisions. The Puget Sound Ambient Monitoring Program (PSAMP), established in 1988, is a multi-agency monitoring program focused on assessing the health of and protecting the Puget Sound Ecosystem (PSWQA, 1996). In 1995, the first comprehensive review of PSAMP was conducted by an external review panel of nationally regarded scientists (PSWQA, 1995). A major result of the review, as related in "Panel Findings and Recommendations" (Shen, 1995), was that PSAMP lacked a "big-picture" focus and was not well integrated. To promote these attributes, the review panel recommended that PSAMP develop a conceptual model that incorporates stressors, key processes, and both ecosystem and management linkages. They asserted that this approach promotes integration of all monitoring efforts and linkage of goals/questions and technical elements of the monitoring design to management needs. The PSAMP Steering Committee, in unanimous agreement with the panel recommendation, responded by establishing a working group to address the formulation of a conceptual model for Puget Sound. In this document we: 1) detail the product of this effort, a matrix from which conceptual sub-models can be drawn; and 2) describe how these products can be used to promote program integration and better linkage with management.

Key aspects defined at the outset for the modeling effort were that it would allow a visual representation of our best understanding of the key components and functions in Puget Sound and human effects on it. The model would identify three levels of relationships: natural processes (e.g., trophic processes, energy transfer, physical relationships); stressors and anthropogenic perturbations (e.g., point and non-point source pollution, harvest, freshwater diversion, marinas); and human management and policy practices (e.g., agencies involved in regulation, criteria levels, management practices, public actions). The model would identify and define linkages within, as well as among, these three levels of relationships.

The model is a communication tool, designed to show where information gaps are, where effort

is being placed, and who or what efforts are involved on a particular ecosystem issue. The model is dynamic in time. We envision that the model will be used to define monitoring efforts and, in turn, the results from monitoring and research from within Puget Sound will be used to refine the model. Use can be viewed in a feedback loop as follows:

1. Provide general scientific agreement for the ecological framework of Puget Sound;
2. Provide a basis to identify gaps in knowledge and understanding;
3. Provide a basis for managers to ask questions, to see the complexity of the information required for answers, and to see relationships between management activities and ecosystem response;
4. Provide a basis for scientists to design monitoring and research programs to answer questions; and
5. Provide context for presenting results.

A feedback loop is established based on using #5 to reinterpret #1 and #2 and then to reassess #3 and #4. Thus, in summary, the fundamental roles of the conceptual model are to:

- Identify and unify the various areas of attention being addressed by PSAMP investigators into specific topics;
- Provide a communication tool, particularly so that one may view the effort of all (not just PSAMP) entities with concerns and/or assessment efforts;
- Explicitly identify linkages within as well as between anthropogenic activities, human management policies, and ecosystem components; and
- Explicitly identify gaps where more effort or awareness should be applied.

Approach

Numerous examples of ecosystem-level conceptual models were identified (Proctor et al., 1980; NOAA, 1983; Clark, 1986; Galveston Bay NEP, 1994). While format and complexity vary substantially, one pattern was that several models are typically needed to describe a system or a program. The models are tailored to serve the messages that each program is making or the audience that is targeted. In such models, there are several categories of information that provide input data for the conceptual model. Several of the categories are represented in Figure 1, which shows the relations between these pools of information. We identified four categories that we wanted represented in our conceptual model that would help us define our monitoring program: Human Activities, Stressors, Ecosystem Components, and Management. Figure 1 also shows how these categories relate to Society and Monitoring programs. Because of the complexity of the information within each category and the variety of linkages, we felt the information could best be handled by placing it in a multi-level matrix. The matrix serves to store, organize and link all input information from each of the categories. The matrix can then be used as a reference tool for construction of visual models. This matrix will be published in a more comprehensive documentation and description of the conceptual model.

The information and linkages portrayed by our visual "conceptual sub-models" are those which were distilled from the matrix. Presentation via the conceptual sub-models is in a more visually informative format and the format can be adjusted to contain more or less detail, as desired, for various audiences.

Matrix Description

Four categories of information have direct bearing on the health of Puget Sound. Each category forms an axis in a linked matrix. The categories are:

1. Components: Components of the greater Puget Sound system are divided into Ecosystem Health and Human Health. Ecosystem health is broken down into the physical, chemical, and biological components of each environment (nearshore, bays and inlets, and open basin). Human health is broken into areas where contact and consumption may be hazardous.
2. Activities: These are activities that impact the Puget Sound environment. Largely these are human actions, but also include natural mechanisms of change within the system. We distinguish construction vs. operation activities, on/over water/shoreline vs. upland activities, and marine vs. freshwater activities. We also distinguish the activity from the resulting stressor(s).
3. Stressors: These are stressors caused by or resulting from the activities described. This category typically contains verb-noun combinations, e.g., "change sediment type" or "increase nutrients."
4. Management: These are governmental regulatory and proprietary programs that have bearing or relevance on the activities listed.

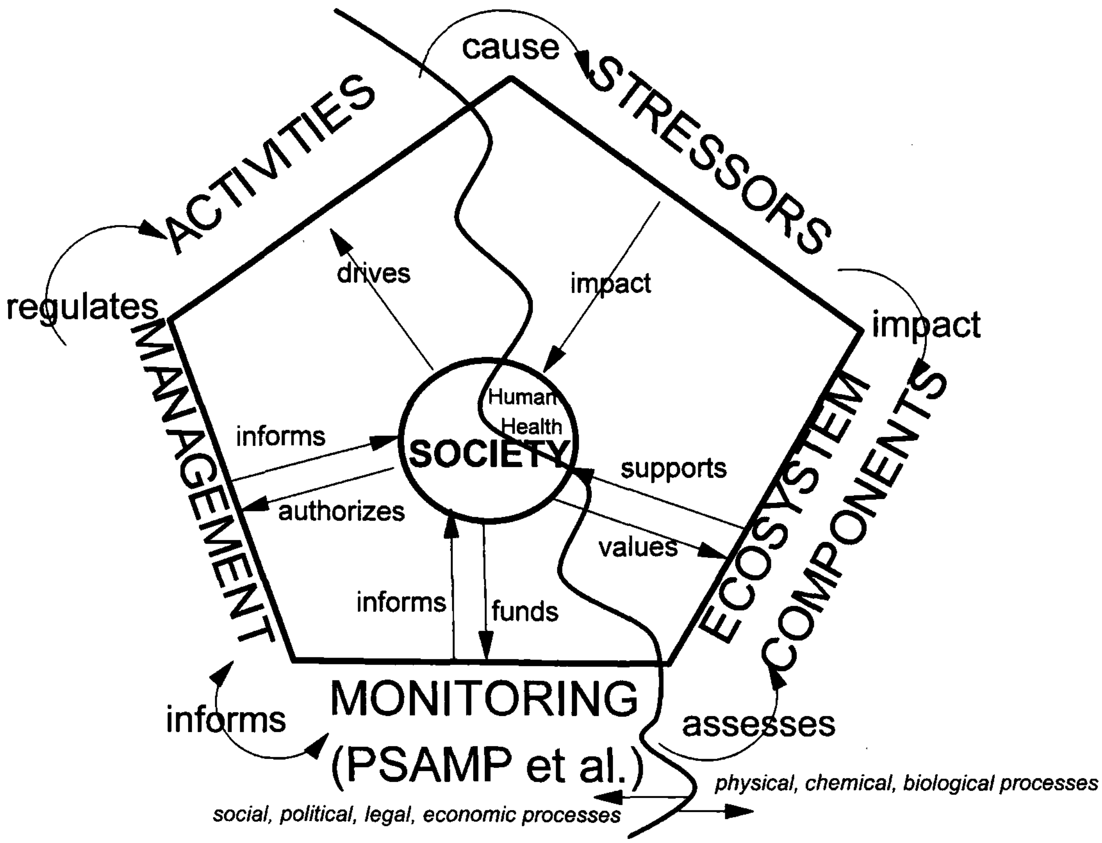

Figure 1. Conceptual model of the relations between key categories involved in environmental monitoring and assessment.

The matrix is primarily described by three associations: activities with management (via regulation); activities with stressors (via causation); stressors with components (via impact). A representation of the relational setup for the matrix is shown in Figure 2. The full matrix and its glossary is currently being printed and will be available in a separate document published by the Puget Sound Water Quality Action Team.

To assess human impacts on the Puget Sound ecosystem, one may first consider the human activities; we have then identified the **stressors** caused by these activities (matrix A), and the management that regulates the activities (matrix B). It must be noted that since both natural and anthropogenic **activities**

can cause the same stress, in some cases the human impact alone cannot be assessed unequivocally. In addition, a smaller matrix (matrix C) has been added because although we are treating Puget Sound as a closed system, it is not. There are external natural inputs to the system that may modify the impact of stressors in a negative or positive way that must also be considered. Stressors are then followed across to identify which of the **components** of the ecosystem or related human health that they impact (matrix D). A glossary to define the terms in all the categories of the matrix follows this document.

At the intersections of the columns and rows in matrices A, B, and C, a check mark appears if there is an association between the two items. Question marks are used in a few cases where the linkage may or may not occur. At the intersections of the headings in matrix D, association is indicated in various ways by use of several symbols. We differentiated direct from indirect associations based on whether the stressor acted directly on that component (e.g., added toxics kill benthic fish) or acted through an intermediary component (e.g., added nutrients change primary production, which affects fish), which we termed indirect.

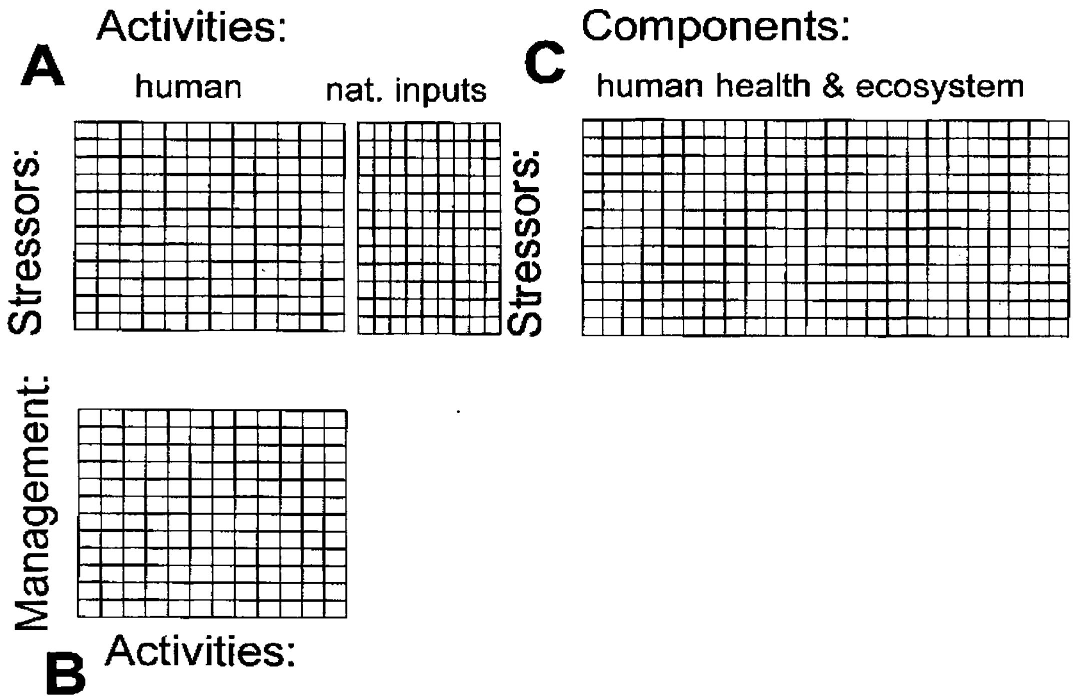

Figure 2. Organizational relations between categories, shown as axes of matrices, used to organize key environmental monitoring.

We divided the Puget Sound natural ecosystem into three non-overlapping areas: nearshore, bay/inlet, and open basin. "Nearshore" is taken to be a region marked by its elevation or depth relative to sea level based on habitat attributes (highest extent of seawater plants to depth of benthic euphotic zone). In this usage, the "bay/inlet" and "open basin" areas both exclude this nearshore portion. These latter two areas differ in their degree of physical enclosure: "bay/inlet" represents the portions of Puget Sound that are ringed by shorelines, somewhat protected, and typically shallower (e.g., Commencement Bay, Sinclair Inlet); whereas, "open basin" represents the deep, typically well mixed basins (e.g., Main Basin, Whidbey Basin). However, no categorization is perfect; places such as Hood Canal have areas with attributes of both bay/inlet and open basin. The purpose of having three areas is to evaluate which impacts change and which stay consistent regardless of physical characteristics.

In summary, the matrix associates various activities with components of Puget Sound ecosystem and human health. We have done this by explicitly identifying which stressors and what management are associated with each activity as well as how resulting stressors are translated to the

various aspects of the ecosystem. These features directly satisfy the key aspects desired for the PSAMP conceptual model, as stated at the outset of this effort.

With this much inherent detail and complexity, modeling the entire system represented in the matrix would likely prove unyielding. However, as described below, the matrix can be used to construct more manageable conceptual sub-models that represent a portion of the entire system, focusing on one stress or one component and identifying all of its linkages. Not only can the matrix be used to construct conceptual (sub)-models, but PSAMP investigators also have used it to identify monitoring topics, integrated questions, and to point to possible environmental indicators.

Matrix Limitations

There are several limitations to the matrix that bear mention before demonstrating its use to create conceptual sub-models. First, no "currency" or specific parameterization (e.g., abundance, carbon, or health) has been defined for the ecosystem component categories. Although the matrix identifies linkages between stressors and ecosystem components as impacts, the nature of the impact is undefined. For instance, a stressor can impact an ecosystem component through a reduction in number/concentration, through substitution or loss of species, through change in individual health, etc. We identified an impact when any type of alteration could be identified. Thus, when constructing models, it cannot be specified from the matrix *a priori* whether the model tracks carbon flow or species impacts. This must be decided by the user, taking into account the underlying mechanisms by which stressors act on components and the responses of the components to stressors.

A second limitation is that when indirect associations are shown, the nature of the indirect association has not been defined in the matrix. A more complete model of the system would indicate relationships between ecosystem components. The user must employ knowledge of ecology and incorporate aspects of ecosystem function into sub-models.

A third limitation is the overlap in and the subjective nature of the three physical ecosystem areas we have defined. We have already acknowledged the difficulty of fitting all Puget Sound areas into one of these three. There are further considerations that must be taken when modeling. While the physical differences in the three areas are appropriate on the scale of vegetation and plankton, many macrobiota (e.g., lingcod, rockfish, grebes) freely swim or fly between areas and may spend time equally or randomly between all three. Thus, when constructing a model for these organisms, one must consider all associations noted and make a sub-model that combines them to a suitable degree for the organism or population. Due to scaling and dilution factors, in most all cases impacts on organisms are worst in the nearshore, followed by bay/inlet, followed by open basin.

Use of the Matrix to Develop Conceptual Sub-Models

Conceptual sub-models are basically a visual representation of the linkages associated with a specified portion of the matrix. This can take any format but both stressor-based and component-based models have particular utility for planning environmental monitoring. Construction of a conceptual sub-model consists of taking a particular heading in the matrix and linking all the headings connected to it. An example of this is shown in Figures 3 and 4, which are stressor-based and component-based models, respectively.

To produce a more integrated and defined monitoring program, within PSAMP the principal investigators evaluated the list of stressors in the matrix and chose the topics shown in Table 1 that would focus on the listed stressors. Examples of conceptual sub-models that illustrate topics are shown in Figures 5 and 6.

Benefits of the Approach

One utility of the modeling exercise is in aligning the monitoring framework and emphases

with the conceptual sub-model, such that gaps are identified. For instance, for the Human Health topic, there are no identified activities or stressors driving the causes of biotoxins. This is a research need. For both the Toxics and Nutrient topics, we have used the model to identify areas where monitoring should be focused. To address these areas, are scoping pilot projects in focused areas: toxics in the lower levels of the food chain (e.g., plankton); and nutrient effects on vascular plants, respectively.

The PSAMP conceptual models are now being used as tools to communicate with management regarding program focus and related policy attributes, with the public regarding the emphasis of PSAMP relative to the entire system, and with other scientists, particularly colleagues involved in similar or related programs and interests in order to forge a better understanding of the environmental status, as well as to form new collaborations.

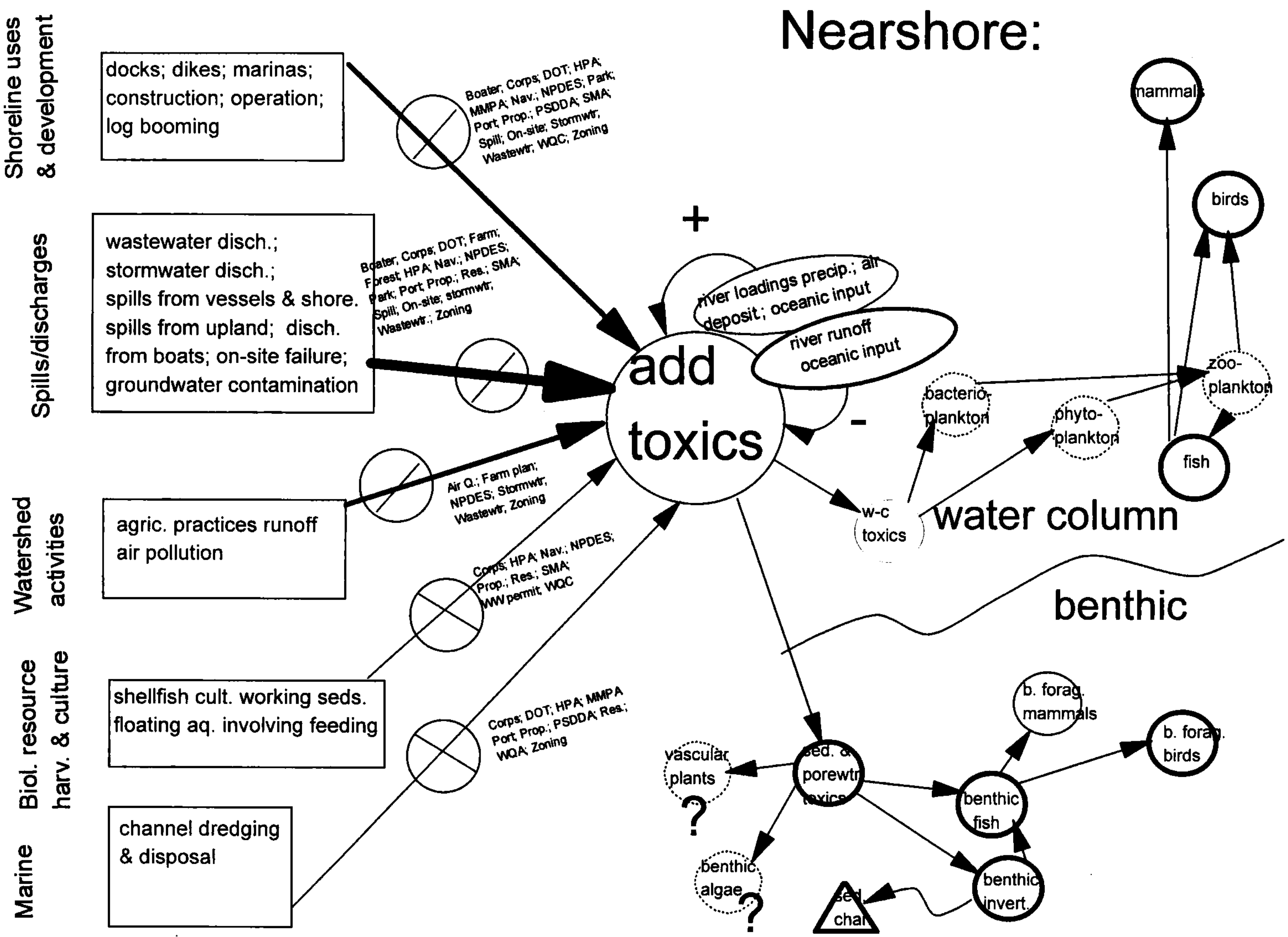

Figure 3. Stressor-based conceptual sub-model for toxics in the nearshore environment. Weighting of line around ecosystem component circles indicates amount of monitoring data available.

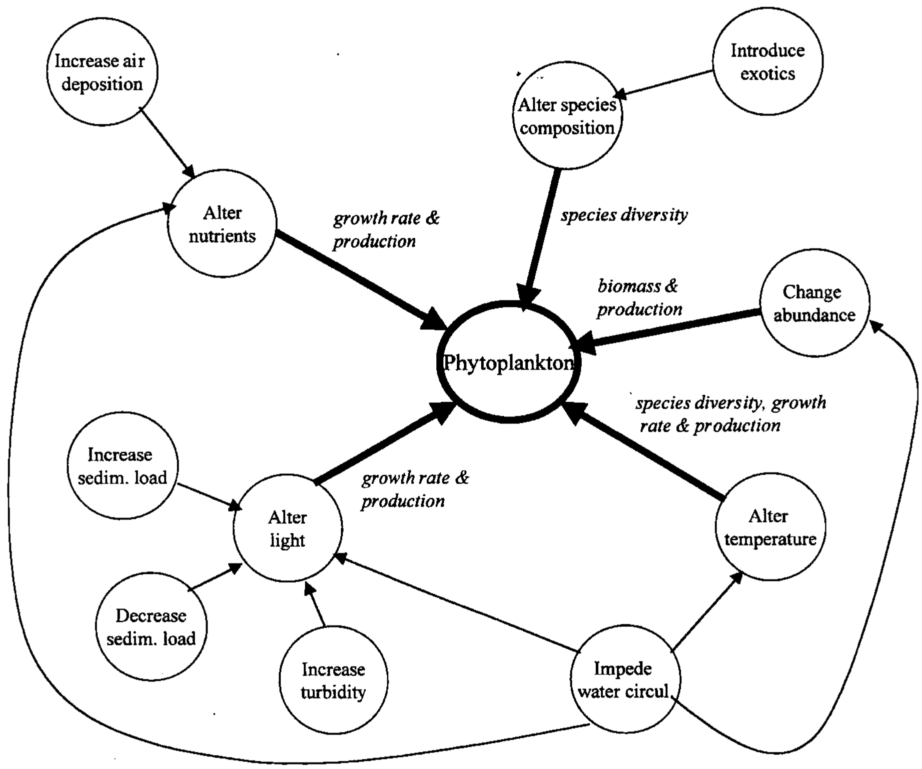

Figure 4a. Component-based conceptual sub-model for phytoplankton. The phytoplankton attributes that are affected by the stressors are shown in italics.

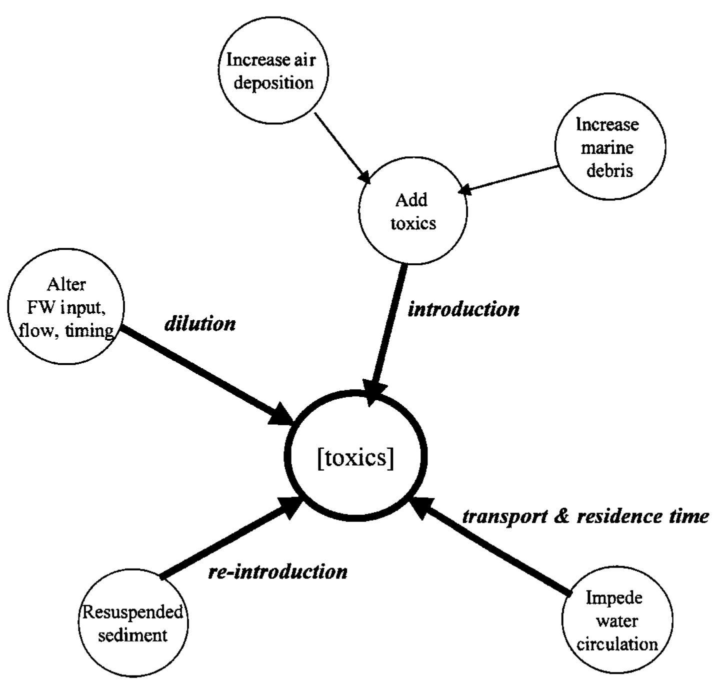

Figure 4b. Component-based conceptual sub-model toxics concentration. The mechanism for the effect is shown in italics.

Table 1. Stressors categorized into topics showing where present PSAMP monitoring effort is currently applied. A sixth topic, "Human Health," addresses contact with and consumption of marine toxics, harmful phytoplankton, and fecals/pathogens.

Topic	Stressor	Current Effort
Contamination		
1. *Toxics*	add toxics	X
2. *Nutrients/Pathogens*	add nutrients	X
	contribute fecal coliform bacteria	X
	increase marine debris	
	increase air deposition	
Physical Environment Alteration		
3. *Inputs to nearshore and pelagic habitat*	increase sediment loadings	X
	decrease sediment loadings	X
	alter freshwater output	X
	increase strength of peak flows	X
4. *Ambient changes in nearshore and pelagic habitat*	alter light transmissivity from turbidity	X
	cause shading (structures)	
	produce noise	
	create physical disturbance via intrusion	
	change depth or shoreline slope	X
	alter sediment type, include: via water transport	X
	physically disturb the sediments	
	resuspend sediment	
	reduce endemic benthic habitat area	X
	sea level change	
	add constructed habitat	X
	alter seawater temperature regime	X
	impede water circulation	X
Organisms		
5. *Marine biota*	extinction/threatening of marine species	X
	introduction of exotic marine species	X
	alter local marine species composition	X
	change marine organism abundance	X

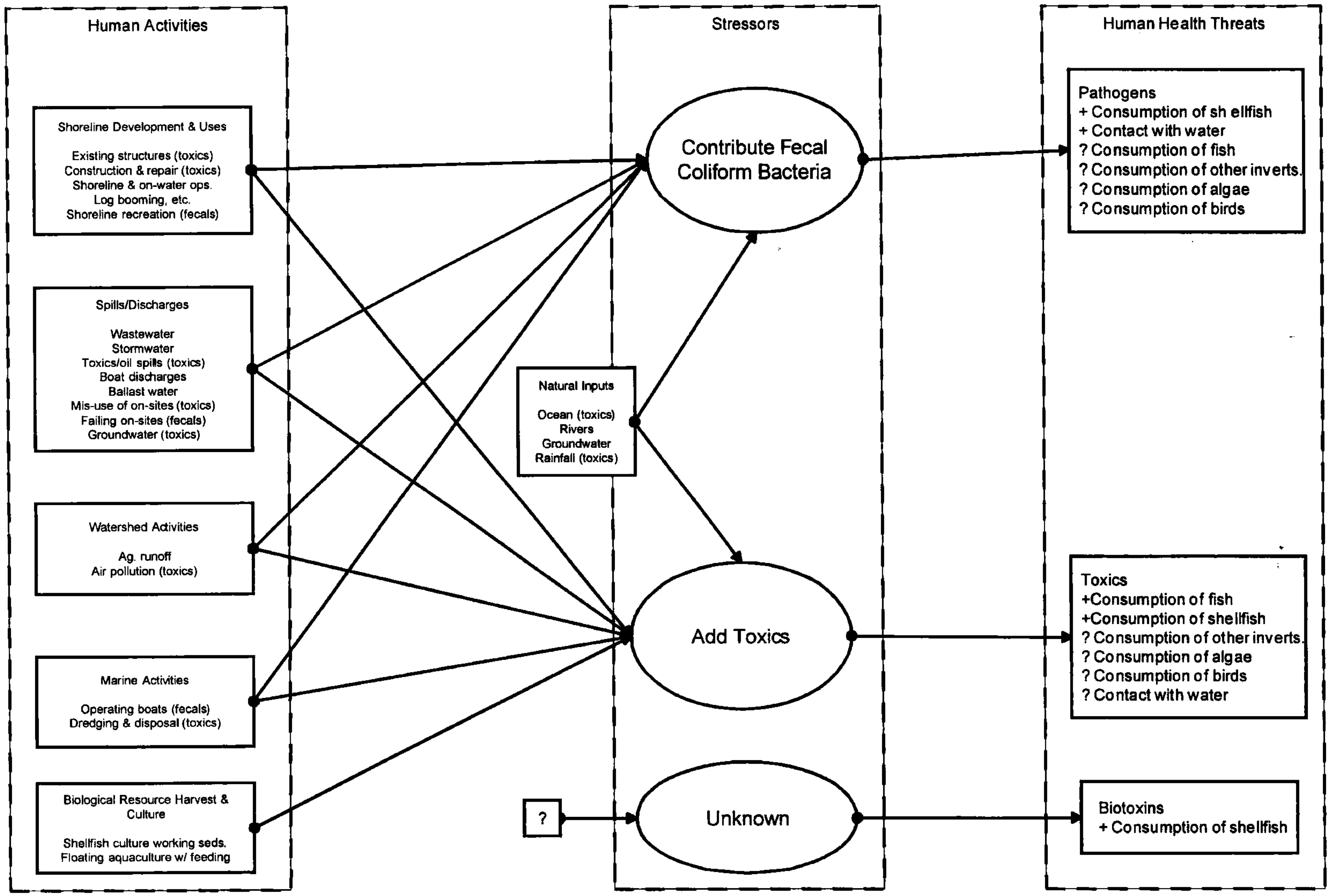

Figure 5. Conceptual model of human health threats in Puget Sound.

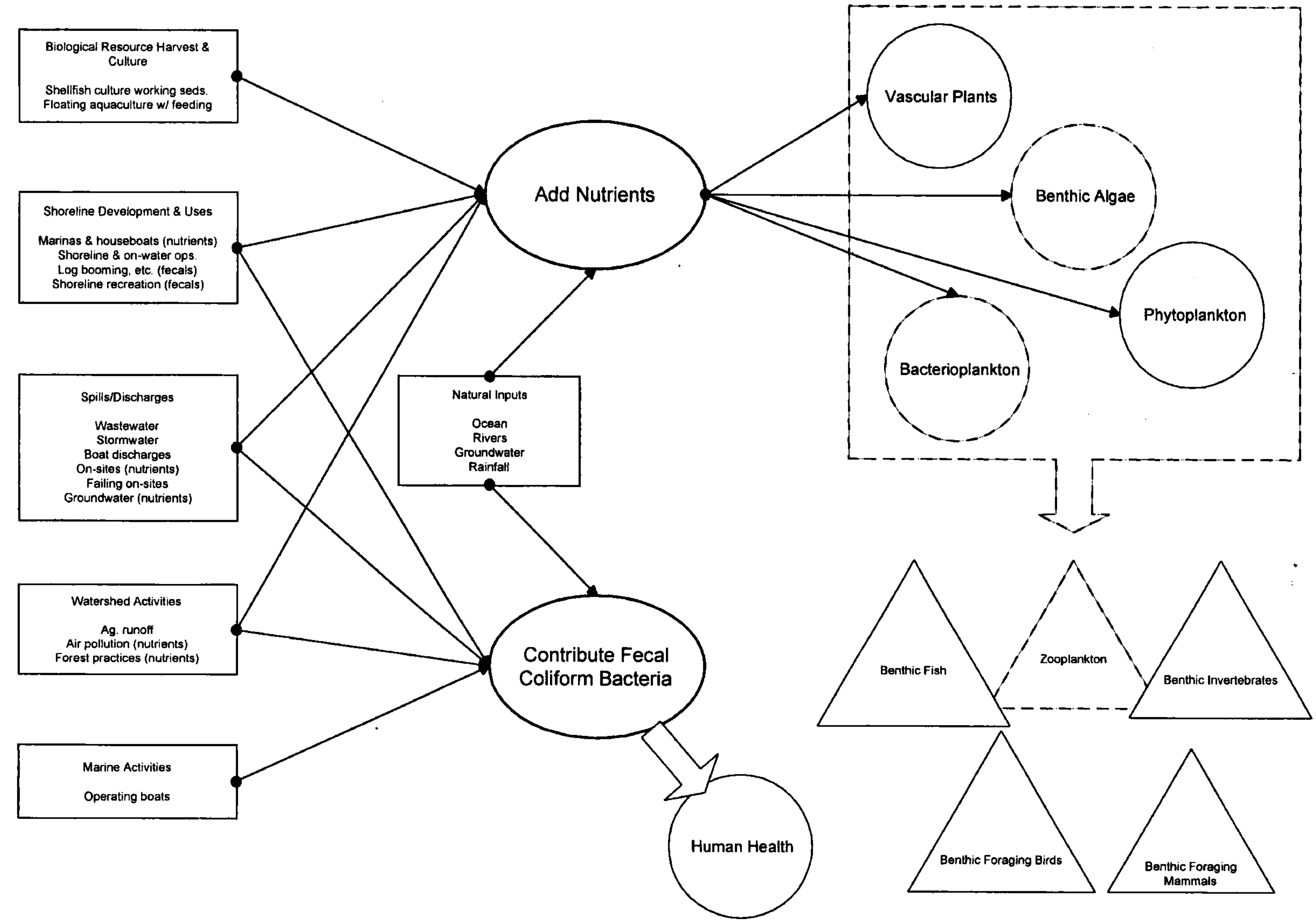

Figure 6. Conceptual model of nutrient and pathogen stresses in Puget Sound.

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The Puget Sound Regional Synthesis Model (PRISM)

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The Puget Sound Region and PRISM

Puget Sound is an integral part of the life of the Pacific Northwest. The beauty and the value of its forests, waters, islands, and shorelines provide an irresistible lure for recreational, aesthetic, and commercial activities. But Puget Sound and its environs are undergoing changes induced by increasing population. At current rates of growth and patterns of urbanization, the region can expect to urbanize land area equal to the city of Tacoma every two years and the city of Portland every five years. Forests, wetlands, and estuarine habitats continue to decrease in area, water resources are over-subscribed, and sediments are increasingly polluted. Together, these effects have led to declining fish populations. If extended over decades, this cumulative degradation will increasingly compromise the viability of the region as a human resource.

One of the most significant challenges for the citizens of the Puget Sound and Georgia Basins is how to balance this population growth while maintaining the environmental integrity so important to the livability and economic viability of the region. Key to finding such a balance is to have a strategy, based on the most sound information possible, to determine the tradeoffs between alternative scenarios for the future. This strategy must include educating the citizens of the region about what the issues and consequences of decisions are, and creating tools to enhance communication among the key players. Current knowledge about Puget Sound is substantial, but fragmented; it is almost entirely descriptive and rarely "prescriptive." In practice, critical issues are divided up amongst multiple agencies and jurisdictions; each is responsible for a piece, but nowhere do they come together.

Developing such a strategy and bringing a common vision and process to the region is the goal of PRISM (the Puget Sound Regional Synthesis Model) a new, and new type, of project based at the University of Washington (UW). PRISM intends to develop and sustain a dynamic and integrated understanding and description of the environmental and human factors that will shape the Puget Sound region as it moves into the 21st century.

PRISM will be a "laboratory and classroom without walls," capable of traveling in time and in space to analyze multiple issues of the region. Its greatest resolution and accuracy will be in confronting the state of Puget Sound today, where access to information is the greatest and, hence, the ability to understand processes and to educate is the greatest. As we develop our ability to model the environment as it exists today (which provides some confidence on the limits of what we know and indicates what directions we must go), we can "zoom in" on periods of the past. The further we go back in time, the more blurry our vision becomes, but in the process we learn what the tradeoffs in analysis are. With the composite information from the present and past, the most challenging task will be to travel into the future, into the 21st century.

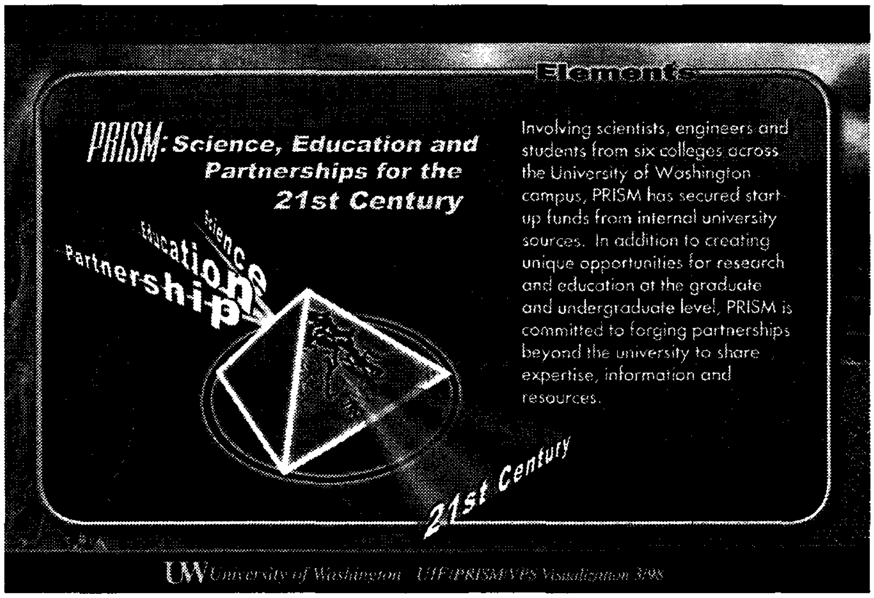
PRISM will address questions critical to the functioning of Puget Sound and surrounding watershed, and assess how the ecosystem responds to natural and human-induced (or anthropogenic)

change. Answering these questions will allow us to focus on the major issues confronting the region:

- How does the landscape and seascape of Puget Sound function both as a natural system and in response to human activities across different time and space scales?
- What are the institutional and social forces that influence how society affects the Puget Sound environment, and how can these forces be better managed to both conserve and develop environmental resources?

PRISM will then consider how to derive and use the resulting information in education and in regional partnerships for the application of the information to regional needs:

- How can the information and understanding obtained through PRISM be used as a means to integrate the component parts of the university and community to offer a high quality interdisciplinary education?
- How can the university best work with other public and private organizations as partners in understanding, managing, and learning about the Puget Sound region?

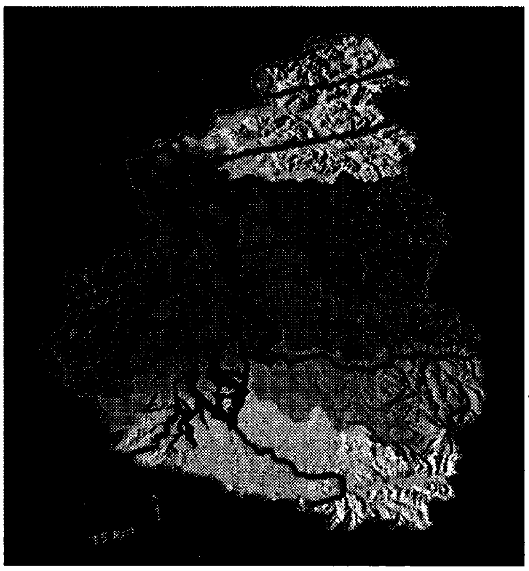


To do this, PRISM requires three concurrent elements:

- Science. Science represents the active synthesis of the multiple sources of information available in the region that must be brought to bear on the issues in an integrative, dynamic, and forward-looking manner. As will be described below, the vehicle for Information will be the creation and maintenance of a "Virtual Puget Sound" (VPS).
- Education. A Puget Sound-driven education program develops and in turn uses the understanding represented by the VPS as the vehicle to conduct the essential and unparalleled level of interdisciplinary learning required across the UW and out to the citizenry. PRISM education efforts are based primarily on the need to be responsive to new mandates to enhance the quality of undergraduate instruction and to provide more opportunities to undergraduates to participate in research activities. Consequently PRISM will provide both content to courses, and resources in the form of VPS information and/or data, running PRISM-supported modeling interfaces, or linking students in classes with researchers involved in PRISM. Conversely, PRISM is set up to benefit by student involvement in that students may be directly involved in data acquisition, model development, and analyses of Puget Sound cases that enhance the "accessibility" of PRISM to other

students. Additionally, efforts to extend both PRISM content and technological resources to K–12 education will take place through pre-service and in-service teacher education opportunities, and through non-traditional educational outlets such as museums and nature centers.

- Partnerships. Data of interest to PRISM extend far beyond those collected by university researchers. PRISM is actively developing partnerships to integrate existing and new information about Puget Sound; these partnerships will facilitate the linking of biophysical and socioeconomic data from many sources including agencies, academic institutions, NGOs, and businesses. PRISM partnerships are conceived as being fully collaborative, where individuals with expertise in a particular topic work together on a common problem, regardless of institutional affiliation (often via the World Wide Web). In this manner PRISM will work to meet the information needs identified in an iterative methodology of user and task analysis. Ultimately PRISM partnerships will be judged not only on the utility of PRISM information, but on the ability to meet common goals that contribute to greater understanding and improved management of the region's natural resources.

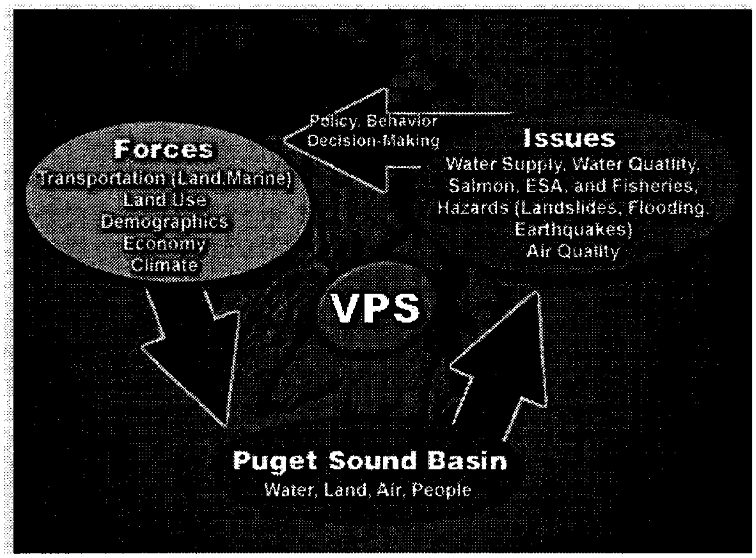


PRISM: Its Domain and Issues

The geographic area encompassed by PRISM includes the drainage basins (with forests, agriculture, and urban land), shorelines and estuaries, and the open water of the Sound itself. This domain requires understanding and tracking of fundamental ecosystem processes and events from mountaintops to ocean floor. Explicit is the recognition that political boundaries cross drainage basin boundaries (where government agencies do not typically operate). While the emphasis will be on Washington State waters, the contiguous ties with British Columbia are implicit. Such a perspective will be crucial as the population of Puget Sound expands and remaining vacant lands between Vancouver and Olympia become developed.

The focus of PRISM is to address a set of major environmental issues of the region that have the common denominator of the movement of water and its constituents from the atmosphere across the landscape and the seascape, and, hence, have a common basis for resolution. Climate and land use practices restructure the water cycle and have major impacts on the economy, biological productivity, and habitability of the region. Understanding and quantifying the water cycle including rainfall patterns, impacts of land use on stream flows and water quality, the impact on wetlands and estuaries and Puget Sound circulation are of first order importance for the Puget Sound community. Specific issues include water supply and quality (allocation, pollutant and contaminant fate, combined sewer outflows, eutrophication of lakes and the Sound), biotic resources (salmon and the Endangered Species Act, habitat integrity and diversity, harmful algae, local fisheries), and air quality. They include the major hazards the region faces, from flooding, landslides, and seismic activity.

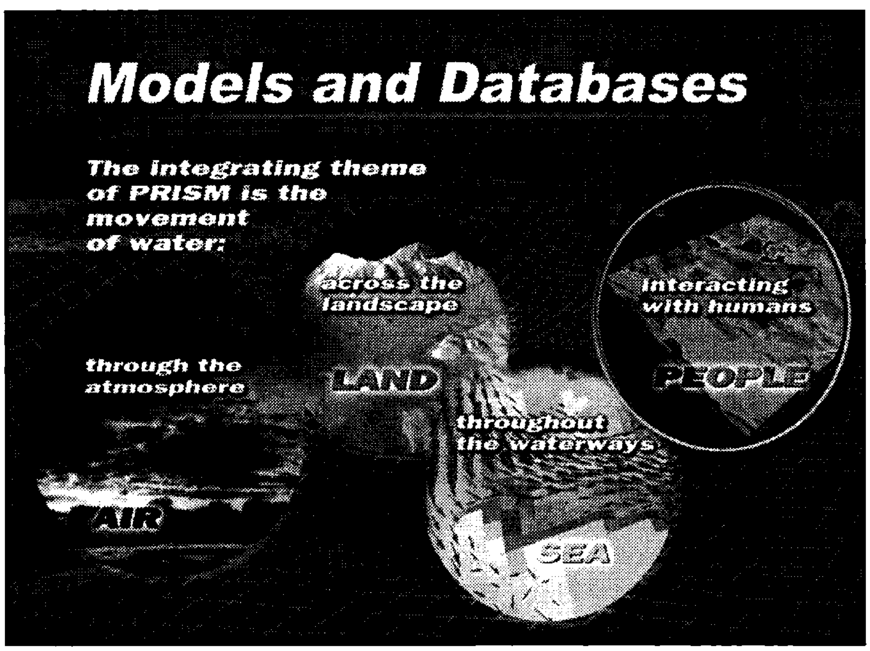
The central operating principle of PRISM is that these regional "forces of change" operate upon a common biophysical structure. We can then treat the "issues" as being a set of tangible consequences created by how forces of change operate upon the Puget Sound Basin. That is, the forces of change are the specific impacts on the environment driven both by social or human actions (e.g., changes in transportation, demography, infrastructure, and technology) and by climatic variations (in rainfall or temperature). The world of Puget Sound is then represented as the "physical template" (below), with multiple time and space scales. It includes the basic structure of the basin (mountains, river basins, flatlands, cities, shorelines, and seafloor), the changes in the basin, which happen over time (the evolution of a forest into a subdivision), and the short-term



dynamics (rainfall patterns causing floods, washing sediments into estuaries).

A Virtual Puget Sound

The primary vehicle for integrating the information requirements for the forces, issues, and Puget Sound Basin is the creation and nurturing of the "Virtual Puget Sound" (VPS). VPS will serve as a gateway to an interactive archive of integrated numerical modeling systems and databases. A series of modules describing the ecological and physical world of Puget Sound will range from basin-wide models and observations of the entire Puget Sound region to ultra-high resolution finite element models suitable

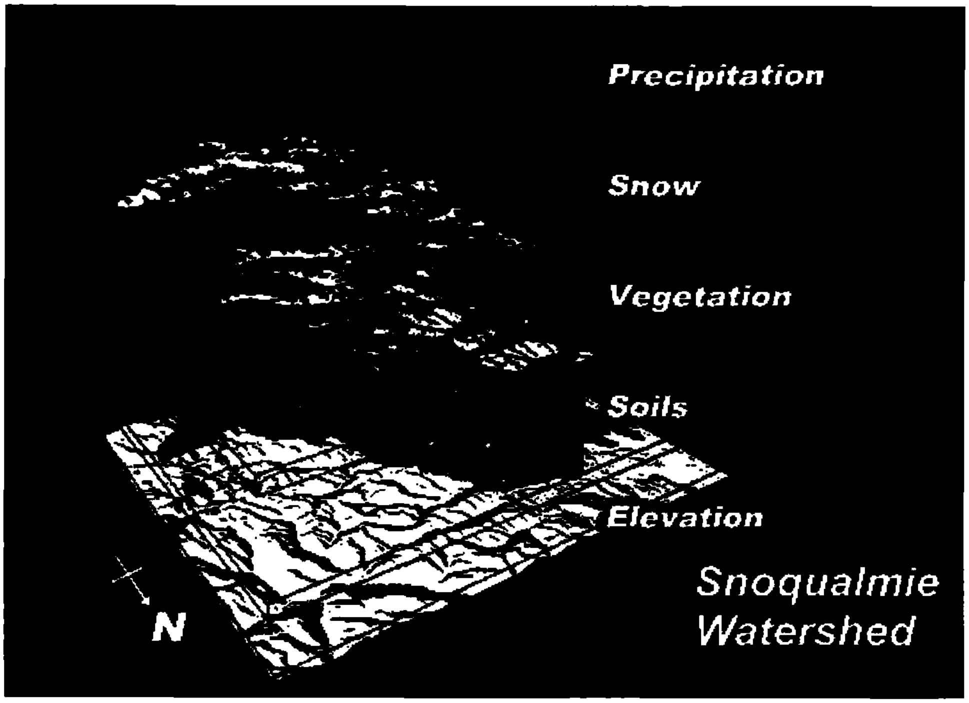


for studies of specific sub-regions.

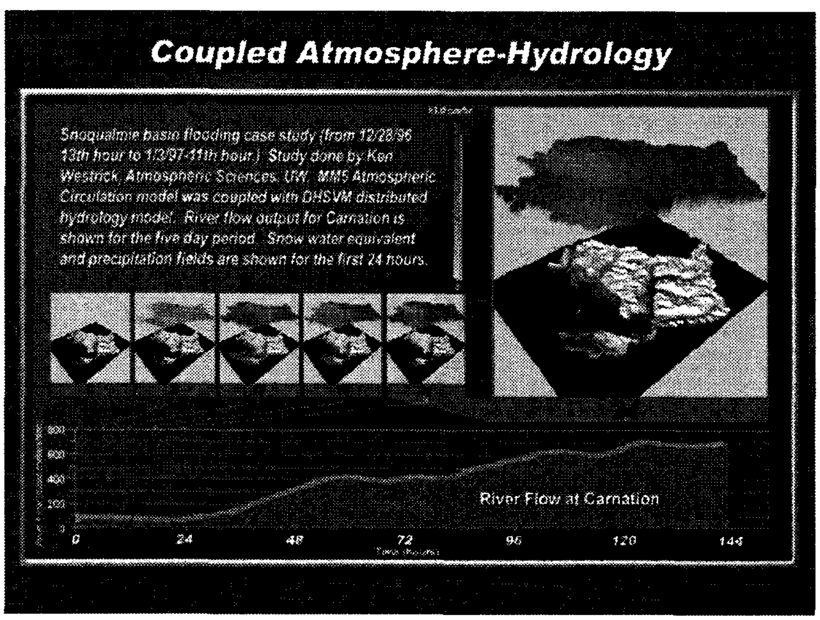
The modules of the VPS will be considered as distinct information systems, containing historical and real-time data (including regional government databases, current information on the state of the region, meteorological and hydrological information, land use, biological inventories, economic and

demographic databases). The modules will also include database tools to access the information, spatial and statistical tools to work with the data, models to project future data states, and a database of literature pertaining to each module. They will link historical information, current conditions, and future projections using the emerging network-based distributed database and model technology. The specific modules of VPS include:

The Physical Template



The basic information for the modules will consist of the "physical template," where the multiple data layers required to describe the land and Sound are assembled in spatial models (illustrated here for the Snoqualmie Basin). The basis of the physical template for the region is a spatial consistent digital elevation model (DEM) on which a flow-direction grid, and a modeled network of streams and basins can be calculated. The physical template is more then a GIS database of thematic layers, such as soils, vegetation, or land use. The physical template is the explicit statement of the relationship between these data layers over both space and time. From this perspective, the physical template becomes a geographically referenced description of the spatial and temporal dynamics of the region.

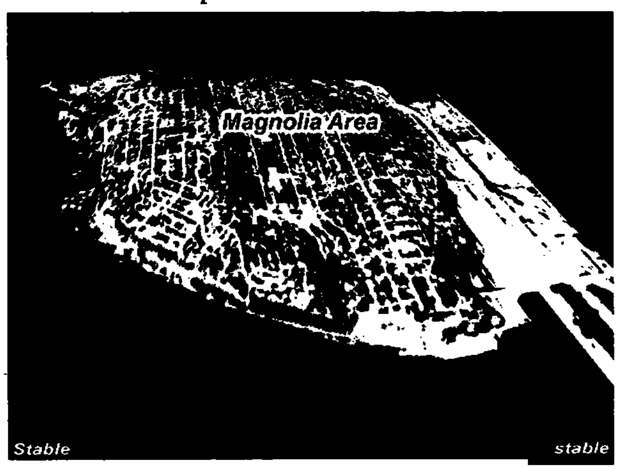


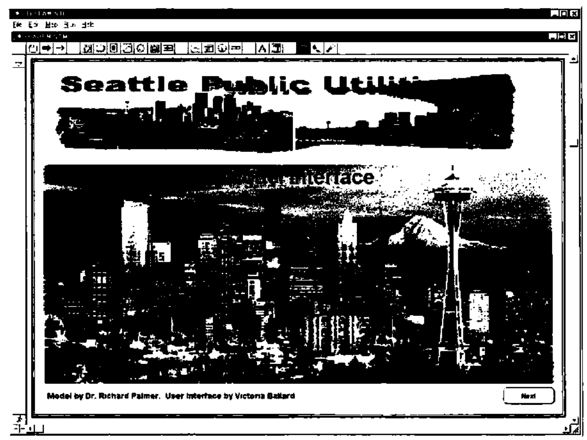
Coupled Atmosphere-Hydrology

An atmospheric regional weather module will provide high temporal and spatial resolution for such information, as rainfall and surface temperature required by the land-surface and water modules. Meteorological forcing for surface hydrology models is provided by the fifth-generation MM5 mesoscale atmospheric model: a limited-area, non-hydrostatic, sigma-coordinate model designed to predict mesoscale and regional-scale atmospheric circulations

and surface exchanges. A consortium of local, state, and federal agencies now runs the MM5 to produce 48-hr weather forecasts at a 12-km spatial resolution for the entire Pacific Northwest and at a 4-km resolution over Washington State. This model is initialized using both observations (both satellite and *in-situ*) and large-scale output from National Weather Service models. Finer-scale surface water movement is represented via the Distributed Hydrology-Soil-Vegetation Model (DHSVM), a physically-based, spatially distributed hydrologic model that explicitly solves the water and energy balance over a topographic grid with cells of typical dimension 30–200 m. DHSVM uses as inputs spatial image data and meteorological forcings from the MM5.

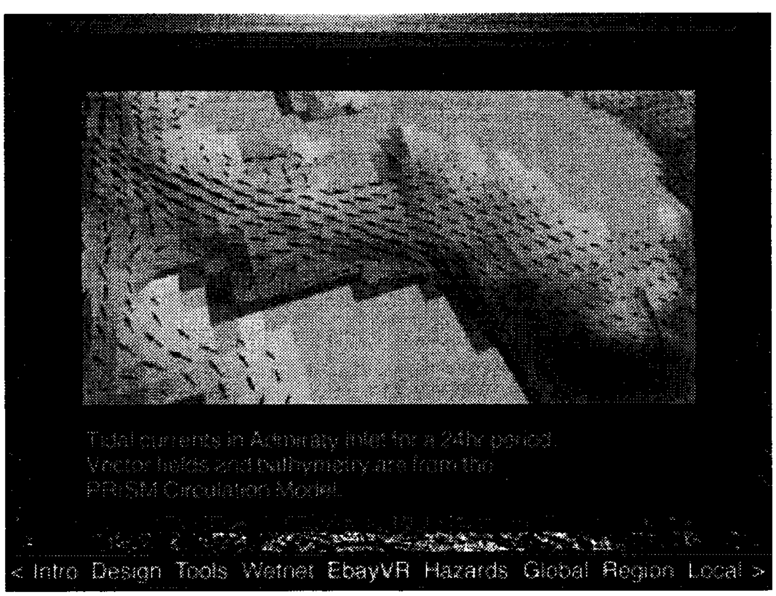
This hydrology model will then be coupled to water resource modeling and hazard prediction (flooding, landslides). Information on water distributions from the hydrology model will be integrated with the requirements of public utilities across the region. Landslides in the Seattle neighborhood of Magnolia, for example, can be predicted from a basic scientific understanding of how slides are produced combined with spatial data sets.





Puget Sound Circulation, Water Quality, and Nearshore habitat

A Puget Sound circulation and water quality module will receive inputs on atmospheric conditions and surfacewater discharge to describe currents in the Sound and potential movements of important nutrients and contaminants. A phytoplankton model, responding to the nutrient availability and to the short wave radiation data supplied from the atmospheric model, will forecast productivity in different locations of the Sound. Each model will be thoroughly validated using data collected in the past and being gathered by various state and local agencies. The Princeton Ocean Model, a three-dimensional, time-dependent, sigma-coordinate, numerical model now used extensively among coastal and estuarine researchers, is being adapted to represent the circulation and ecosystem structure of Puget Sound. This model includes realistic bathymetry and an accepted parameterization of turbulent mixing. It is forced by realistic tides and river flows (from the hydrology modules), and has been run to simulate Puget Sound circulation and stratification for a model year. Biology and chemistry are being incorporated.



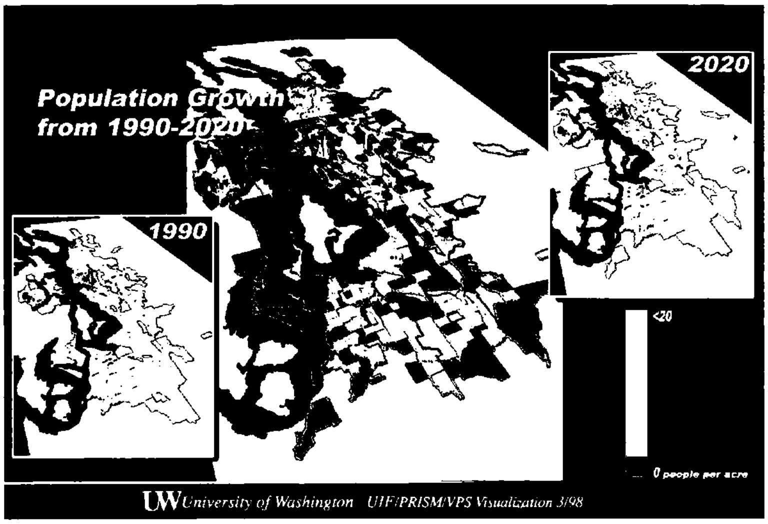
PRISM will complement these efforts by conducting observations at crucial points using moored and bottom-mounted arrays, shipboard observations (both from the UW research vessels and through collaborative arrangements with shipping concerns such as Washington State Ferries), and by means of remote sensing. Of particular importance will be monitoring of the entrance of Admiralty Inlet from the Strait of Juan de Fuca, through a combination of moorings and shipboard observations, temperature, salinity and current to give a boundary condition to the circulation model, and flux of nutrients into the Sound.

The focus of the marine biological communities module will be to describe nature and extent of historical change in shoreline, inter- and shallow water sub-tidal habitat, with an emphasis on major commercial and recreational fisheries species (e.g. bivalves, crabs, shrimp, flatfishes, salmonids). A hierarchy of marine habitats will be defined for inter-and sub-tidal areas of Puget Sound based on major assemblages of flora and fauna, physio-chemical attributes, as linked to riverine and watershed features. Spatial distribution will be derived from present day resource atlases and historical documents back to the 1870s. These databases will be used to build simulations derived from the "Circulation and Physical Processes" group to study outcomes of scenarios for remedial actions (e.g., return of diked land to wetlands habitat for salmon), or consequences of further human perturbations (e.g., spread of exotic species).

The Human Dimension

The PRISM human dimension currently includes two components: (a) the impacts of human action on the biophysical system, and (b) the socioeconomic effects of environmental change in the Puget Sound. Human decisions will be treated explicitly through the development of an urban ecosystem model (UEM), ultimately addressing how population changes over time might affect the region.

This model will predict the environmental stresses associated with urban development and land use change under alternative demographic, economic, and policy scenarios. Urban development is a dynamic outcome of the interactions between the choices of many actors including households, businesses, developers, and governments. These actors make decisions that alter the patterns of land use and human activities. UEM will be designed to model spatially explicit processes that link these decisions to changes in the Puget Sound biophysical structure. PRISM will build on existing urban simulation models to predict four types of human-induced environmental stressors: land conversion, resource use, emissions, and other physical modifications that affect the habitat of specific species. The initial focus will be on modeling changes in land use and land cover. The model is object-oriented and builds on an existing urban simulation model (UrbanSim) to predict the location behaviors of households, businesses, and developers. Production and consumption behavior will be added to households and businesses and linked through a grid representation of land to infrastructure and natural systems. Governmental choices about urban growth, zoning, infrastructure, and pollution control policies are exogenous to the model. The core location model in UrbanSim will also be revised from its current aggregate structure to one based on micro-simulation, and from a zone description of space to one based on a high resolution grid structure. Using UrbanSim predictions as an input, changes in land use and cover will be modeled using a multinomial logit-model based on a set of land use and cover determinants including original use, accessibility, environmental conditions, cost of conversion, and policy constraints. The model will provide parameter estimations to calculate land use and cover transition probabilities. The output of the urban ecosystem model will serve as the input to several biophysical models including the hydrology, hill-slope stability, water quality, atmospheric, and aquatic and terrestrial ecosystem models.



A socioeconomic impact model will estimate the direct and indirect effects of the changes in the Puget Sound biophysical structure on property value, income, health and quality of life. The current focus of the socioeconomic model is on the potential impacts of flood and landslide events. Stakeholders concerns and interests that are related to these impacts are also mapped to identify the differential impacts on various economic and social groups.

The biophysical and the human dimensions will be linked through an integrated assessment model. Development of such an integrated model will provide a framework to answer relevant policy questions for the Puget Sound. More specifically scientists in such areas as marine affairs, urban planning, engineering, and resource management will work with natural systems scientists to develop an integrated view that satisfies both the natural and social sciences. This integrated framework will constitute the basis to describe causal relationships and interactions at a variety of spatial and temporal scales. A decision-support system will be devised to evaluate the impacts of current trends and alternative futures in terms of social and economic benefits and costs, as well as in terms of environmental values and benefits. This system could be used to determine who pays for, and who benefits from, changes in land use, resource management and other regulatory actions that affect Puget Sound. The integrated assessment model and decision support system will allow policy makers, students, and researchers to determine scenarios that maximize benefits to the Puget Sound environment and to human society. Changing how society relates to Puget Sound will require changes in the behavior of large organizations and institutions, businesses, households, and individuals. PRISM will develop models and analyses of regulations and behavioral patterns that determine land use, resource management, and waste disposal in order to make better predictions of the impact of future actions on the natural environment and on social benefits. From these predictive models, policy makers, scholars, and citizens can devise best practices for human activities and behaviors to sustain and enhance the Puget Sound environment over the next century.

The process of collaborations visualization, communication, and computer graphics have advanced to a stage that cooperative work between units is viable and the distribution of graphical output to university and community groups is possible. PRISM will determine how to make a heterogeneous collection of complex scientific models available in a uniform way and provide general mechanisms for coupling them. It will examine how to handle multiple scales in both space and time, and how to visualize the vast amount of information required. To promote consensus on purposes and to assess our current state of knowledge and capabilities, a goal of the VPS is to serve as a forum for evaluation of alternative approaches. The execution of VPS will be via the World-Wide Web.

What is Unique About PRISM?

PRISM is intended to help address issues played out daily in the newspapers across the region. The establishment, verification, and continuous refinement of the Virtual Puget Sound environment will provide a powerful tool for education and outreach. Model output will be made available in real time and retrospectively through the World Wide Web and other media. Once improved to a state of considerable realism, the VPS will be used for evaluating the effects of changes in land management and other environmental changes. By contributing to the capability of the region to make optimum use of its resources, the sustainability and viability of the Puget Sound Basin should be promoted.

The Georgia Basin Ecosystem Initiative

Bruce Kay
Environment Canada, Pacific and Yukon Region

Introduction

Ecosystem initiatives represent a major component of Environment Canada's contribution toward a more sustainable future for Canada. The department works with a broad spectrum of governments and communities of interest in pursuit of shared objectives. Ecosystem initiatives also advance the achievement of Environment Canada's goals and objectives, including those reflected in the department's overall priorities:

- ensuring Canadians have clean air and water;
- protecting and conserving nature; and
- studying climate change.

Ecosystem initiatives facilitate the achievement of results that can be superior to those achievable through either the department acting alone or through traditional partnerships. They have the capacity to lever government resources, focus science, coordinate efforts, generate public and political support and produce the informed decisions necessary to address ecosystem issues. Moreover, they help to build the capacity of the department and all of the partners and communities involved.

Ecosystem initiatives are cooperative ventures in geographically targeted ecosystems, and are guided by the principles that generally guide departmental programs and activities, including:

- Ecosystem approach—recognizing the interrelationships between land, air, water, wildlife, human activities, etc.;
- Science—basing decisions on sound science, both natural and social, combined with local and traditional knowledge;
- Government partnerships—governments working together to achieve the highest level of environmental quality for all Canadians;
- Citizen/community-based—engaging individuals, communities, aboriginal peoples, industry and governments in the design and implementation; and
- Pollution prevention—it is better for the environment and often more cost effective to prevent pollution from occurring rather than clean up after ecosystems have been degraded.

Ecosystem initiatives also offer opportunities to experiment with innovative forms of governance. They combine the perspectives, interests and resources of citizens and governments with those of the private and non-profit sectors. They promote shared responsibility and accountability for issues while providing a means for federal and provincial governments to deliver on their responsibilities and accountabilities.

Georgia Basin Ecosystem Initiative

The Georgia Basin ecosystem encompasses an area of approximately 135,000 km^2 and includes the land and inland sea (Georgia Strait, Puget Sound, and the Strait of Juan de Fuca) defined by the heights of land formed by the Vancouver Island Ranges, the Coast Ranges, the Cascades, and the Olympic Mountains. The boundary is marked roughly by Campbell River in the north, Olympia in the south, Hell's Gate in the Fraser Canyon to the east, and Race Rocks in the Strait of Juan de Fuca to the west.

The Basin has one of the most rapidly expanding urban/suburban concentrations in North America.

With its location and high quality of life, it has emerged as a major gateway to the Pacific Rim group of countries.

Two-thirds of British Columbia's population (2.7 million people) and three-quarters of its labor force live in the Georgia Basin. In 1990, the combined Washington/B.C. population in the Basin was 5.7 million. The population within the Georgia Basin is projected to about double in the next 20 years. Development pressures are now imposing unprecedented levels of physical, chemical, and biological stress on the ecosystem. Unchecked, the increasing level of human imposed stress will put at risk the very ecosystem conditions that provide the foundation of the region's economy, the health of individuals, and the overall quality of life that attracted people here in the first place. With appropriately managed growth, a remarkable opportunity exists for this region to provide an example of how to do it right—of providing for the well-being of people and their communities while maintaining (as a minimum) or preferably improving, ecosystem health.

For all of these reasons, the Georgia Basin ecosystem has been assigned a high priority for attention by Environment Canada, and other federal and provincial counterparts. It is here where the greatest concerns are, it is here where the greatest gains are to be made, and it is here where successful resolution of sustainability issues will have the greatest impact on similar problems facing other parts of British Columbia, Canada, and abroad.

The Georgia Basin Ecosystem Initiative (GBEI) has not emerged in a vacuum. Rather, it has been built on decades of activity at the federal, provincial, regional district, and municipal level. For example, the experience/successes of the Fraser River Estuary Study and resulting Fraser River Estuary Management Plan (FREMP), the Fraser River Action Plan (FRAP), the Fraser River Management Plan (FRMP) and its successor the Fraser Basin Council (FBC), the province's Georgia Basin Initiative (GBI), the evolving Growth Management Plans of the Regional Districts, the BC-Washington Environmental Cooperation Council, and a number of more discrete federal and provincial programs have all provided essential input.

Initiative Purpose, Vision, and Goals

The GBEI is an evolving, results- and science-based integrated action plan. Its ***purpose*** is to enhance coordination and collaboration amongst the many government and non-government stakeholders while achieving measurable improvements in:

- conditions affecting environmental health and human well-being;
- the capacity of individuals and families, businesses and organizations, and all orders of government to deal with issues of sustainability; and
- the efficiency and effectiveness of government.

The initiative is taking an approach to dealing with priority issues that is holistic, long-term, consensus-based and inclusive of affected stakeholders. In doing so, it is attempting a new approach to problem solving and the delivery of government services. It is not simply doing more of what has been done already over the years.

A draft ***vision*** statement for the initiative has been developed collaboratively with participants. It is:

VISION

Managing Growth to Achieve Healthy, Productive, and Sustainable Ecosystems and Communities

Similarly, the following three broad ***goals*** have been identified:

GOALS

- to enhance environmental health
- to enhance society's capacity to achieve sustainability
- to enhance human well-being

The purpose, vision, and goals all recognize the multi-faceted, environmental, social, economic, cultural and political nature of achieving progress toward sustainability. In addition, the network of collaborators that is being established reaches well beyond traditional "environmental" partners to include many government agencies and businesses and organizations of civil society that capture this breadth of perspective.

The initiative includes three primary streams of activities (Figure 1). In each stream and in each program element, environmental, social, economic, cultural, and political implications play a role in program design, implementation, and assessment of success.

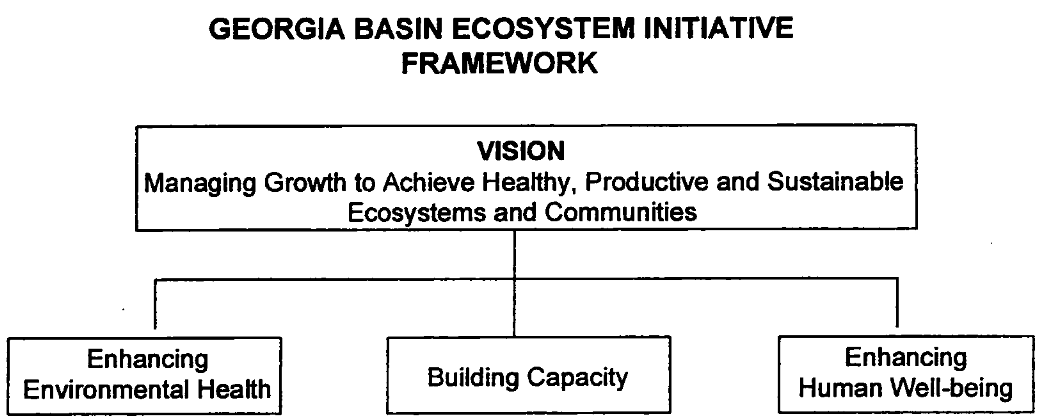


Figure 1. Organization of the Georgia Basin Ecosystem Initiative.

Issues

Key issues facing the Georgia Basin ecosystem that will be addressed by the initiative include:

- the pervasive issue of growth management;
- Lower Mainland air quality (emissions, resulting conditions and implications, solutions);
- continuing point and non-point discharges to surface water and related programs of pollution prevention;
- contamination of ground water, particularly by agricultural activities;
- sewage contamination of shellfish production areas;
- toxic chemicals, in particular endocrine disrupters;

- degradation and loss of coastal and uplands habitat (often from urban and suburban expansion) and the related land management regimes; and
- shifting responsibilities between federal, provincial, and local orders of government, and the need for effective cooperation and collaboration.

To address these issues, multi-agency working groups have been established to develop detailed action plans. Figure 2 summarizes the action plans currently under development.

Actions to Enhance Environmental Health	Actions Contributing to a Sustainable Society	Actions to Enhance Human Well-being
• Achieving Clean Air	• Transferring Science to Decision-makers	(Under development by Health Canada in collaboration with provincial health partners)
• Achieving Clean Water	• Mobilizing Communities	
• Conserving and Protecting Nature	• Measuring Progress	
	• Governanace Models	

Figure 2. Lower Fraser/Georgia Basin Ecosystem Initiative action plans.

Next Steps

During 1998, the action plans will be completed and implemented with a number of partners. Annual review of progress will be facilitated through an interagency coordination mechanism, and priorities and strategies will be evaluated based on the action plan results and emerging issues in the basin.

The Puget Sound/Georgia Basin International Task Force: Transboundary Protection of Marine Resources

David Peeler
Washington State Department of Ecology

Les Swain
BC Ministry of Environment, Lands, and Parks

Abstract

The Puget Sound/Georgia Basin International Task Force (Task Force) was created under the auspices of the Environmental Cooperation Agreement signed by the Governor of the State of Washington and the Premier of the Province of British Columbia in 1992. The Task Force consists of voluntary representatives from several state, provincial, and federal resource agencies, and it coordinates and collaborates on activities affecting shared marine resources. An early action of the Task Force was to assist an appointed Marine Science Panel to review the status of shared marine resources and make findings and recommendations for their protection. Since the release of the Science Panel"s recommendations in 1994, the Task Force has been responding to the highest-priority recommendations. The Task Force, together with several topic-specific Workgroups, has developed technical information on several of the recommendations (exotic species, habitat loss, protection of marine plants and animals, and marine protected areas) and has published several technical reports. The Task Force and Work Groups are also developing strategies and management recommendations to address these high priority issues. We will present information on how technical details are being transformed into management actions, while other papers being presented at this workshop will deal with the specific process for each topic area where this is progressing. The Task Force has also conducted some transboundary work on marine monitoring, strategic planning, and toxic discharges. The Task Force will continue to press ahead on these issues, and, as resources allow, tackle other priority recommendations as well.

Fisheries and Oceans Canada—Science and the New Oceans Act

Dr. John Pringle
Fisheries and Oceans, Canada

Abstract

Canada's federal government has the mandate, granted under the British North America Act (1872) and retained in Canada's 1982 Constitution, to manage marine renewable resources in most nearshore and all offshore waters. The Oceans Act, promulgated in 1997, provides a modern framework for ocean resource management and marine environmental protection in all Canadian waters. The Act's Part II sets out principles to guide the Department of Fisheries and Oceans' management efforts, and it provides basic tools and authorities with which to design and implement the new oceans management process. The Oceans Management Strategy includes sustainable development, management of oceans as ecosystems, integrated management of activities impacting marine waters, and the use of the precautionary approach. The Act, during its formative stages, was strongly influenced by the Department's Science Sector; advice based on scientific research is thus the underpinning of the department's thrust. Initial research initiatives are described.

PUGET SOUND RESEARCH '98

SESSION 1A

THE WATERSHEDS UPSTREAM

Session Chair:

Derek Booth

Center for Urban Water Resources, University of Washington

The Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion

Christopher W. May
Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington

Background

In the Pacific Northwest (PNW), as in many areas of North America, urban development is rapidly expanding into areas containing much of the remaining natural aquatic ecosystems. In the Puget Sound lowland (PSL) ecoregion, the natural ecosystems most directly affected by urbanization are small streams and associated wetlands. These ecosystems are critical spawning and rearing habitat for several species of native salmonids (both resident and anadromous), including cutthroat trout (*Oncorhynchus clarki*), steelhead trout (*O. mykiss*), coho salmon (*O. kisutch*), chum salmon (*O. keta*), chinook salmon (*O. tshawytscha*), pink salmon (*O. gorbuscha*), and sockeye salmon (*O. nerka*). These fish, especially the salmon species, are of great ecological, cultural, and socio-economic value to the peoples of the PNW. Despite this value, wild salmonids are in considerable jeopardy of being lost to future generations (Figure 1). Over the past century, salmon have disappeared from about 40% of their historical range, and many of the remaining populations (especially in urbanizing areas) are severely depressed (Nehlsen et al., 1991). There is no one reason for this decline. The cumulative effects of land-use practices, including timber harvesting, agriculture, and urbanization, have all contributed significantly to this widely publicized "salmon crisis."

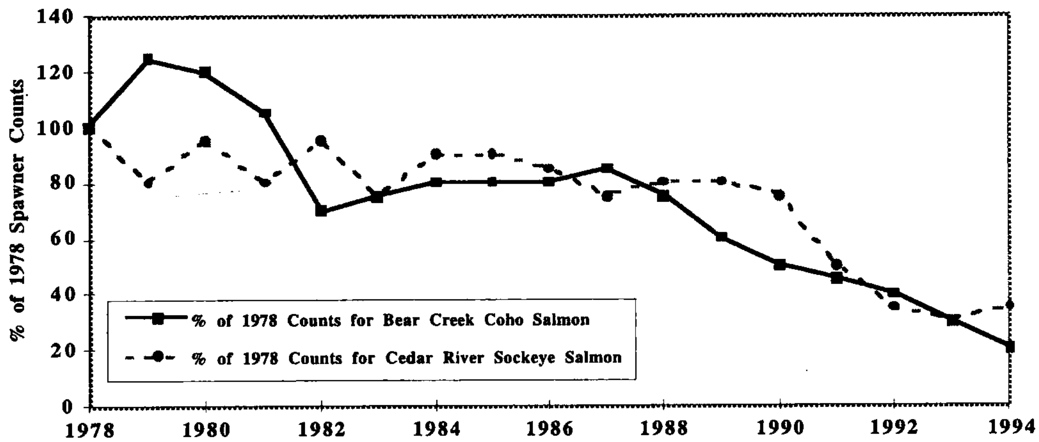


Figure 1. Representative data showing the decline in salmon stocks in the Puget Sound lowland (PSL) region, using 1978 as the base year for spawner counts (Washington State Department of Fisheries data).

The effects of watershed urbanization on streams are well documented (Leopold, 1968; Hammer, 1972; Hollis, 1975; Klein, 1979; Arnold et al., 1982; Booth, 1991). They include extensive changes in basin hydrologic regime, channel morphology, and physiochemical water quality. The cumulative effects of these alterations has produced an instream habitat that is significantly different from that in which salmonids and associated fauna have evolved. In addition, development pressure has a negative impact on riparian forests and wetlands, which are essential to natural stream functioning. Considerable evidence of these effects exists from many studies of urban streams in the PNW (Perkins, 1982; Richey, 1982; Steward, 1983; Scott et al., 1986; Booth, 1990; Booth and Reinelt, 1993; Taylor, 1993). Nevertheless, most previous work has fallen short of establishing cause-and-effect relationships between physical and chemical variables resulting from urbanization and the response of aquatic biota.

The most obvious manifestation of urban development is the increase in impervious surface area and the corresponding loss of natural vegetation. Land clearing, soil compaction, encroachment on riparian corridors, and modifications to the surface-water drainage network all typically accompany urbanization. Watershed urbanization is most often quantified in terms of the proportion of basin area covered by impervious surfaces (Schueler, 1994; Arnold and Gibbons, 1996). Although impervious surfaces themselves do not generate pollution, they are the major contributor to the change in basin hydrologic regime that drives many of the physical changes affecting urban streams. Basin imperviousness and stormwater runoff are directly related (Schueler, 1994). The two most common measures of imperviousness are total impervious area (%TIA) and effective impervious area (%EIA). The distinction between the two lies in the linkage between the impervious surface and the drainage network. Total impervious area includes all impervious surfaces in the watershed. Effective impervious area includes only those that are directly connected to the surface drainage system. Total and effective basin imperviousness are typically proportional to each other (Alley and Veenhuis, 1983; Beyerlein, 1996). In previous studies, a TIA of about 10% has been identified as the level at which impairment of the stream ecosystem begins (Klein, 1979; Steedman, 1988; Schueler, 1992; Booth and Reinelt, 1993). Recent studies also suggest that this potential threshold may apply to wetlands as well (Taylor, 1993; Horner et al., 1996).

Study Design

A key objective of the PSL stream study was to identify the links between landscape-level conditions and instream environmental factors. This objective included defining the functional relationships between watershed modifications and aquatic biota. The goal was to provide a set of stream-quality indices for local resource managers to use in managing urban streams and minimizing resource degradation due to development pressures. The assumption is that given populations or communities of organisms (native salmonids) can be maintained at a specified level by sustaining a certain set of habitat characteristics, which, in turn, depend on an established group of watershed conditions. An additional objective was to identify any possible thresholds of watershed urbanization related to instream salmonid habitat and aquatic biota. The study was designed to establish the links between landscape-level conditions, instream habitat characteristics, and biological integrity. A conceptual model of this design is illustrated below:

Watershed and Riparian Characteristics	⇒	**Instream Habitat Conditions**	⇒	**Aquatic Biota**

A subset of 22 small-stream watersheds (Figure 2) was chosen that represented a range of development levels from relatively undeveloped (reference) to highly urbanized. Total impervious surface area, because of its integrative nature, was used as the primary measure of watershed urbanization. The attributes of the stream catchments were established using standard watershed analysis methods, including data from geographic information systems (GIS), aerial photographs, basin plans, and field surveys. Impervious surface coverage, riparian integrity, physical characteristics of the instream habitat, chemical water-quality constituents, and aquatic biota were analyzed on both watershed and stream-segment scales. Stream flow was continuously monitored by local agencies on 10 of the study streams. Chemical water-quality monitoring (base flow and storm events) was conducted at 23 sites on 19 of the study streams. Biological sampling (macroinvertebrates) was performed in 31 reaches on 21 of the study streams. Extensive surveys of instream physical habitat and riparian zone characteristics were made on 120 stream segments that included all 22 PSL streams; each survey represented local physiographic, morphologic, and sub-basin land use conditions from the headwaters to the mouth of each stream. Salmonid abundance data were obtained from public, private, and tribal sources.

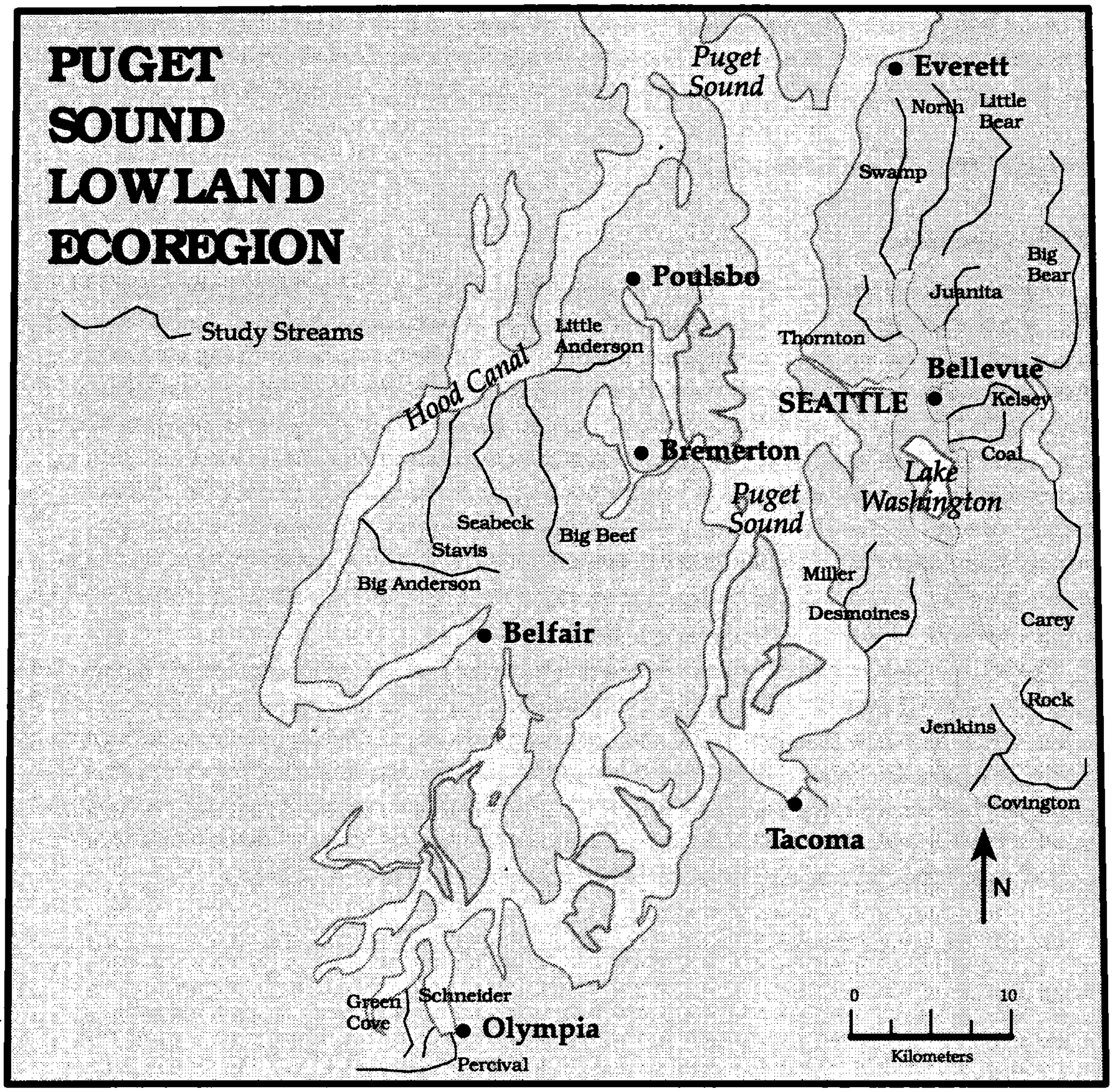


Figure 2. Puget Sound lowland (PSL) ecoregion.

All streams were third order or smaller, ranging in basin area from 3 to 90 km^2, with headwater elevations less than 150 m. Stream gradients were less than 3.5% (most were < 2%). The study watersheds represented the two general types of geologic and soil conditions found in the Puget Sound region. These types are mainly a result of the last glacial period (15,000 years ago). All but three of the watersheds were dominated by poorly drained glacial till soils, with the remaining basins being dominated by glacial outwash soil types (moderately well drained). In the undisturbed, natural forested condition, PSL catchments are capable of providing adequate natural storage of precipitation in the surficial "forest-duff," and little runoff results. Therefore, in natural PSL watersheds a subsurface-flow hydrologic regime dominates. Development typically strips away this absorbent layer, compacts the underlying soil, and exposes the underlying till. Also lost is a significant amount of interception storage as well as evapotranspiration potential provided by the regionally dominant coniferous forest. The typical suburban development in the PNW has been estimated to have roughly 90% less storage capacity than naturally forested areas (Wigmosta et al., 1994). The latest (1990) stormwater mitigation and best-management practices (BMPs) would, at most, recover only about 25% of the original storage capacity (Barker et al., 1991). Because these standards affected very little new development that occurred between 1990 and the

start of this study in 1994, the basin conditions observed largely reflected the pre-1990 situation, and little effective stormwater control was present. Therefore, no significant conclusions could be drawn from this research about the effectiveness of current stormwater controls (BMPs) and regulations.

Results and Discussion

Watershed Conditions

Watershed imperviousness ranged from undeveloped (TIA < 5%) to highly urbanized (TIA > 45%). Imperviousness (%TIA) was the primary measure of watershed development; however, other measures of urbanization were investigated. Calculating impervious surface area can be costly, especially if computerized methods like GIS are utilized. In addition, the land-use data required for calculating %TIA may be unavailable or inaccurate. As part of this study, a low-cost alternative to using impervious area was also investigated. Analysis demonstrated that results were very similar whether development was expressed as impervious area or as road density (Figure 3). This is especially relevant in that the transportation component of imperviousness often exceeds the "rooftop" component in many land-use categories (Schueler, 1994). A recent study in the Puget Sound region has shown that the transportation component typically accounts for over 60% of basin imperviousness in suburban areas (City of Olympia, 1994).

The PSL study (Cooper, 1996) confirmed that watershed urbanization significantly changes basin hydrologic regime (Leopold, 1968; Hollis, 1975; Booth, 1991). The ratio of modeled 2-year storm flow to mean winter base flow (Cooper, 1996) was used as an indicator of development-induced hydrologic fluctuation (Figure 4). This discharge ratio is proportional to the relative stream power and thus is representative of the hydrologic stress on instream habitats and biota exerted by stormflow conditions relative to baseflow conditions. Modification of basin hydrologic regime was found to be one of the most influential changes resulting from watershed urbanization in the PSL region.

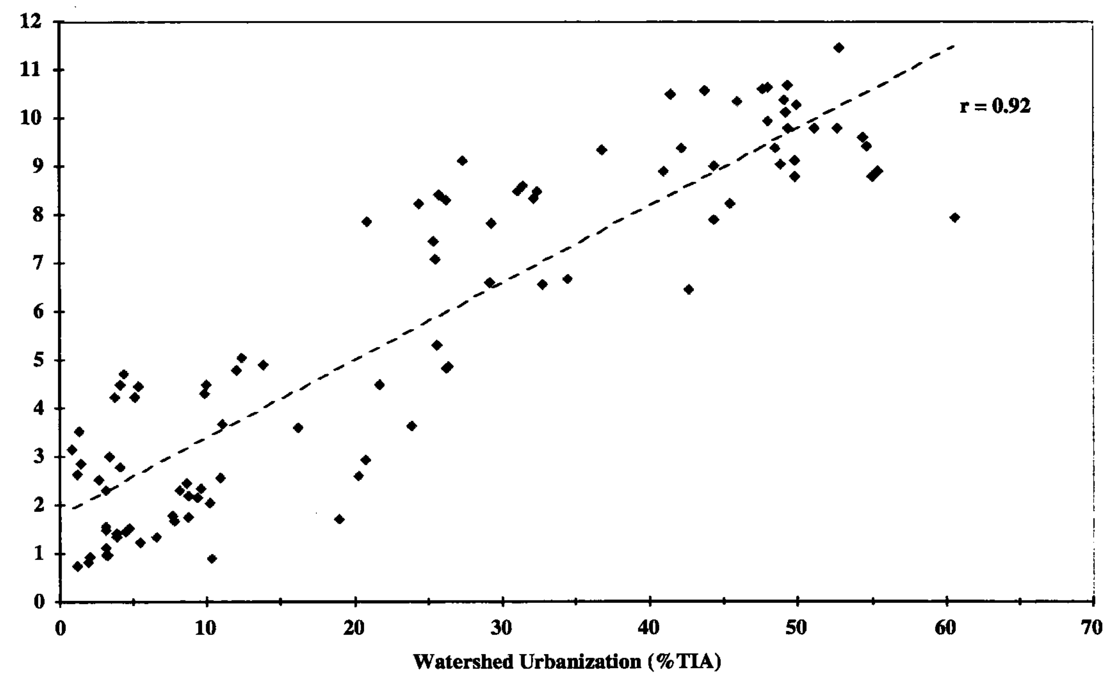


Figure 3. Relationship between urbanization (%TIA) and sub-basin road density in Puget Sound lowland (PSL) streams.

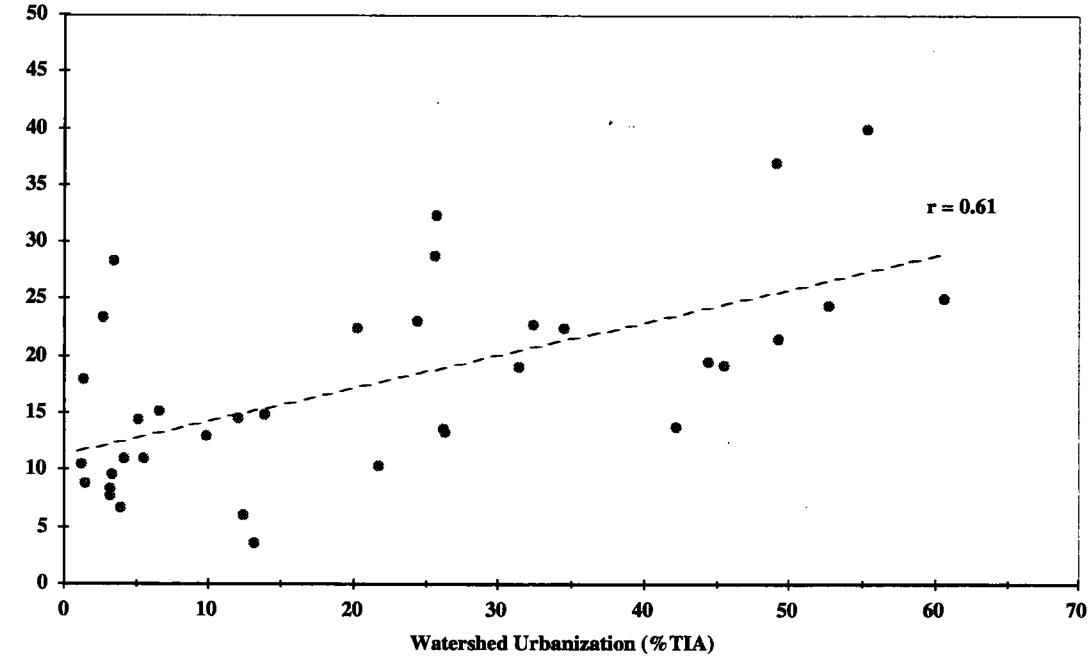


Figure 4. Change in basin hydrologic regime with urbanization in Puget Sound lowland (PSL) streams as indicated by the ratio of 2-year storm flow to winter base flow.

In addition to increasing basin imperviousness and the resulting stormwater runoff, urbanization also affects watershed drainage density (kilometers of stream length per square kilometer of basin area). This was first investigated by Graf (1977). In the PSL study, natural, predevelopment drainage density (DD) was calculated using historic topographic maps. This was compared with the current, urbanized DD, which included the loss of natural stream channels (mostly first-order and ephemeral ones) due to grading or construction and the increase in artificial "channels" due to road crossings and stormwater outfalls. The ratio of urban-to-natural DD was used as an indicator of urban impact (Figure 5).

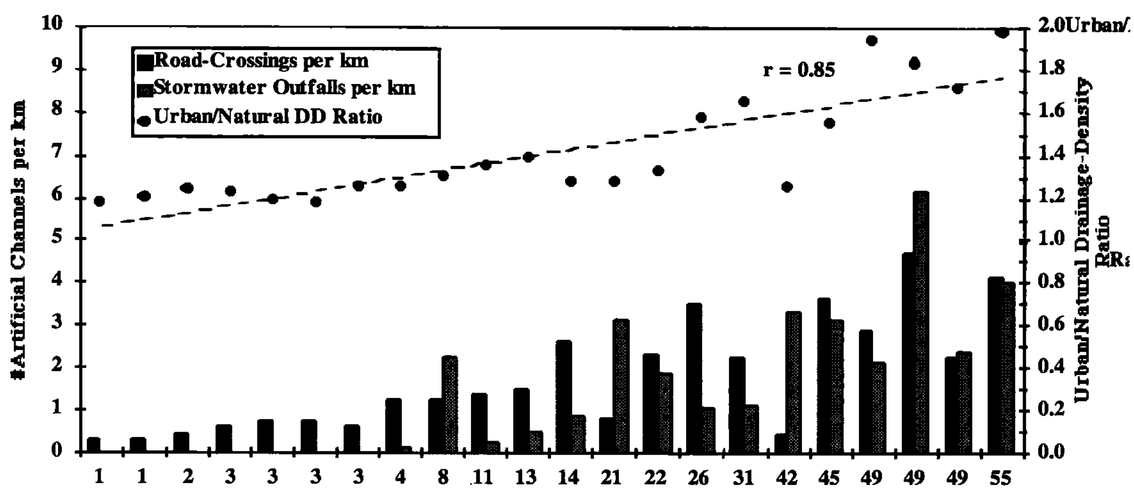


Figure 5. Change in watershed drainage density (DD) due to the effects of urbanization on the stream channel network.

Riparian Conditions

The natural riparian corridors along PNW streams are among the most diverse, dynamic, and complex ecosystems in the region. Natural riparian integrity in the PNW is characterized by wide buffer zones, a nearly continuous corridor, and vegetation dominated by a mature, coniferous forest. Riparian corridors are key features that significantly control environmental conditions in stream ecosystems (Naiman, 1992). The extent of the riparian zone, the level of control that it exerts on the stream environment, and the diversity of its functional attributes are mainly determined by the size of the stream and its longitudinal position within the drainage network (Naiman et al., 1993). Well developed, morphologically complex flood plains are often an integral part of the riparian corridors surrounding PNW streams and rivers (Naiman, 1992). The riparian corridor is frequently disturbed by flooding, creating a naturally complex landscape. Ecological diversity in riparian zones is maintained by the natural disturbance regime (Naiman et al., 1993).

Not surprisingly, riparian conditions were also strongly influenced by the level of development in the surrounding landscape. The impact of development on riparian corridors varies widely, depending on the type and intensity of land use, the degree of disturbance to streamside vegetation, and the residual integrity of the riparian zone. Under past land-use practices, increased development has led to a decrease in the width of the buffer zone, fragmentation of the riparian corridor, and an overall degradation in riparian quality. In general, until 1993, development regulations in the PNW did not specifically address riparian buffers. Sensitive-area ordinances, now in effect in most local municipalities, typically require riparian buffers 30–50 m (100–150 ft) wide. These recently adopted regulations had little influence on the urbanized streams in the PSL study. In general, wide riparian buffers were found only in undeveloped or rural watersheds (Figure 6). The actual size of riparian buffer needed to protect the ecological integrity of a stream system is difficult to establish (Schueler, 1995). In most cases, the minimum buffer width "required" depends on the resource or use of interest and the quality of the existing riparian vegetation (Castelle et al., 1994).

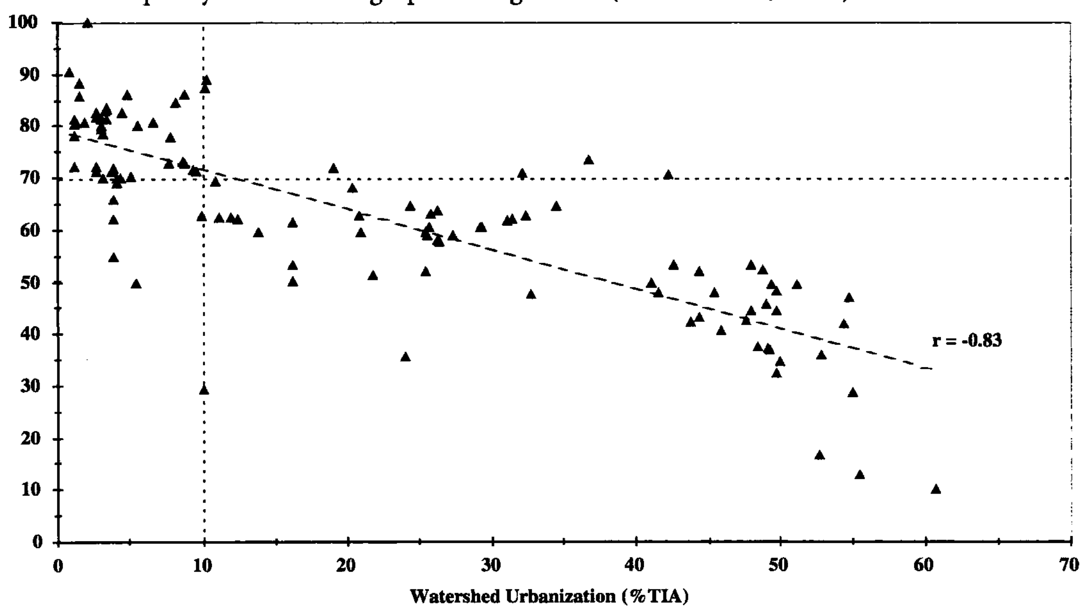


Figure 6. Relationship between riparian buffer width and basin urbanization (%TIA) in Puget Sound lowland (PSL) streams.

Encroachment into the riparian buffer zone is pervasive, continuous, and extremely difficult to control. At the same time, riparian forests and wetlands, if maintained, appear to significantly mitigate some of the adverse effects of development. A buffer width of less than 10 m is generally considered functionally ineffective (Castelle et al., 1994). The fraction of riparian buffer less than 10 m wide was used as a measure of riparian zone encroachment. In general, only natural, undeveloped basins (TIA < 10%) had

streams where less than 10% of the buffer zone was in a nonfunctional condition. As watershed urbanization (%TIA) increased, riparian buffer encroachment also increased proportionally. For the most highly urbanized streams (TIA > 40%) in this study, generally more than 40% of the buffer zone was in a nonfunctional condition.

The longitudinal continuity of the riparian corridor is at least as important its lateral width. A nearly continuous riparian zone is the typical natural condition in the PNW (Naiman, 1992). The riparian corridor in urban watersheds can become fragmented from a variety of human influences; the most common and potentially damaging being road crossings. In the PSL stream study, the number of stream crossings (roads, trails, and utilities) increased in proportion to the intensity of basin development. All but one undeveloped stream (TIA < 10%) had, on average, less than one riparian break per kilometer of stream length. Of the highly urbanized streams (TIA > 40%), all but one had more than two breaks per kilometer. Based on current development patterns in the PSL, only rural land use consistently has less than two breaks in the riparian corridor per kilometer of stream length. In general, the more fragmented and asymmetrical the buffer, the wider it needs to be to perform the desired functions (Barton et al., 1985).

The riparian zone was also examined on a qualitative basis. Mature forest, young forest, and riparian wetlands were considered "natural" as opposed to residential or commercial development. From an ecological perspective, mature forest and riparian wetlands are the two most ecologically functional riparian conditions in the PNW (Gregory et al., 1991). In the 22 PSL streams, riparian maturity was also found to be strongly influenced by watershed development. Only in natural streams (TIA < 5%) was a substantial portion of the riparian corridor mature forest (40% or greater), whereas urban streams consistently had little mature riparian area. In addition, none of the urbanized PSL streams retained more than 25% of their natural floodplain area.

Chemical Water Quality

Chemical water-quality constituents were monitored under baseflow and stormflow conditions. Baseflow conductivity was found to be strongly related to the level of basin development (Figure 7). Coal Creek was a confirmed outlier owing to the residual effects of historical coal mining in its headwaters. While conductivity is a nonspecific chemical parameter, it is a surrogate for total dissolved solids and alkalinity and an excellent indicator of the cumulative effects of urbanization (Olthof, 1994). Storm event mean concentrations (EMC) of several chemical constituents were found to be related to both storm size (magnitude and intensity) and basin imperviousness (Bryant 1995). However, water-quality criteria were rarely violated except in the most highly urbanized watersheds (TIA > 45%). Figure 7 also shows the relationship between urbanization and the EMC of total zinc (TZn). Total phosphorus and total suspended solids showed similar relationships. Zinc and lead in the sediment also showed a relationship with urbanization, again with the highest concentrations occurring in the most developed basins, although all were still below sediment-quality guidelines. As with other recent studies (Bannerman et al., 1993; Pitt et al., 1995), these findings indicate that the chemical water quality of urban streams is generally not significantly degraded at low impervious levels, but it may become a more important factor in streams draining highly urbanized watersheds.

Instream Salmonid Habitat Characteristics

Large woody debris (LWD) is a ubiquitous component in streams of the PNW. No other structural component is as important to salmonid habitat, especially for juvenile coho (Bisson et al., 1988). LWD performs several critical functions in forested lowland streams, including dissipation of flow energy, protection of stream banks, stabilization of stream beds, storage of sediment, and providing instream cover and habitat diversity (Bisson et al., 1987; Masser et al., 1988; Gregory et al., 1991). Although the influence of LWD may change over time, both functionally and spatially, its overall importance to salmonid habitat is significant and persistent. Both the prevalence and quantity of LWD declined with increasing basin urbanization (Figure 8). At the same time, measures of salmonid rearing habitat, including percentage of

pool area, pool size, and pool frequency, were strongly linked to the quantity and quality of LWD in PSL streams. While LWD quantity and qualitywere negatively affected vy urbanization, even many of the natural, undeveloped streams lacked LWD (especially very large LWD). This deficit appears to be a residual effect of historic timber-harvest and "stream-cleaning" activities. Nevertheless, with few exceptions, (habitat restoration sites), high quantities of LWD occurred only in streams draining undeveloped basins (TIA < 5%). It appears that stream restoration in the PSL should include enhancement of instream LWD, including addressing the requirement for long-term recruitment of LWD.

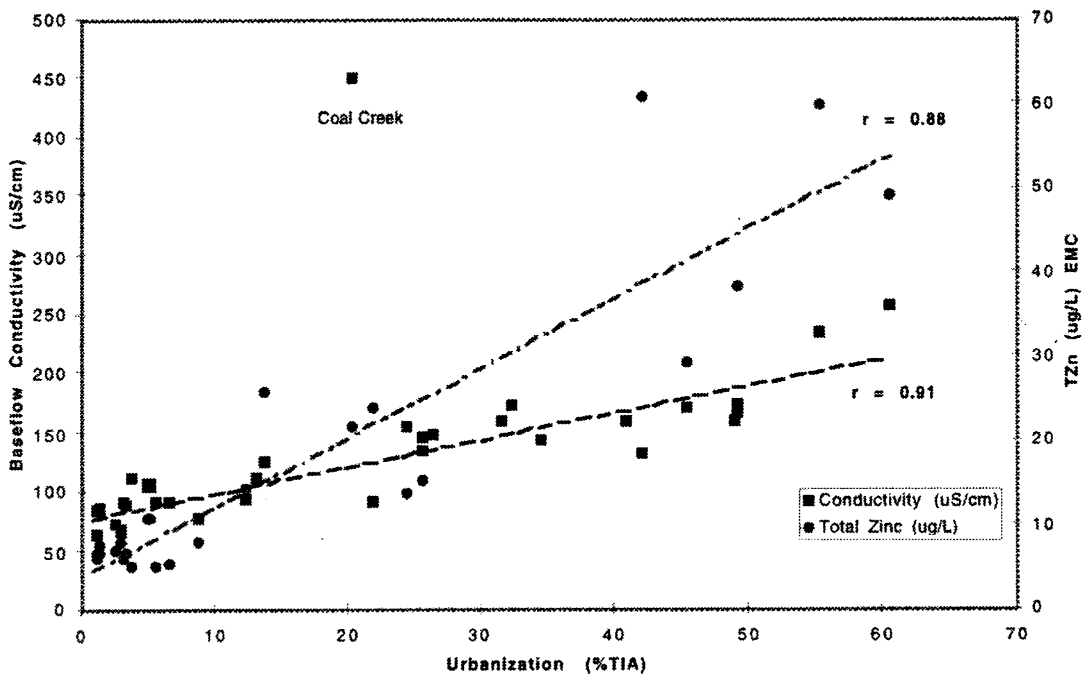


Figure 7. Baseflow conductivity and storm event mean concentration (EMC) of total zinc (TZn) compared with watershed urbanization (%TIA) in Puget Sound lowland (PSL) streams.

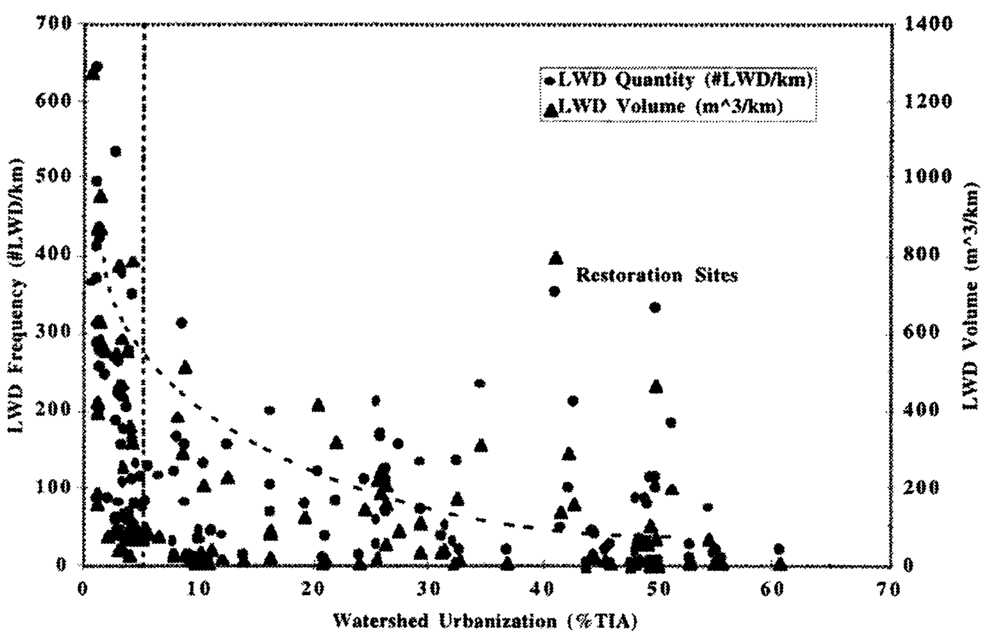


Figure 8. LWD quantity and watershed urbanization (%TIA) in Puget Sound lowland (PSL) streams.

An intact and mature riparian zone is the key to maintaining instream LWD (Masser et al., 1988; Gregory et al., 1991). The lack of functional quantities of LWD in PSL streams was significantly influenced by the loss of riparian integrity (Figure 9). In general, except for restoration sites, higher quantities of LWD were found only in stream segments with intact upstream riparian corridors. In addition, LWD quality was strongly influenced by riparian integrity. Very large, stable pieces of LWD (greater than 0.5 m in diameter) were found only in stream segments surrounded by mature, coniferous riparian forests. This natural LWD historically provided stable, long-lasting instream structure for salmonid habitat and flow mitigation (Masser et al., 1988).

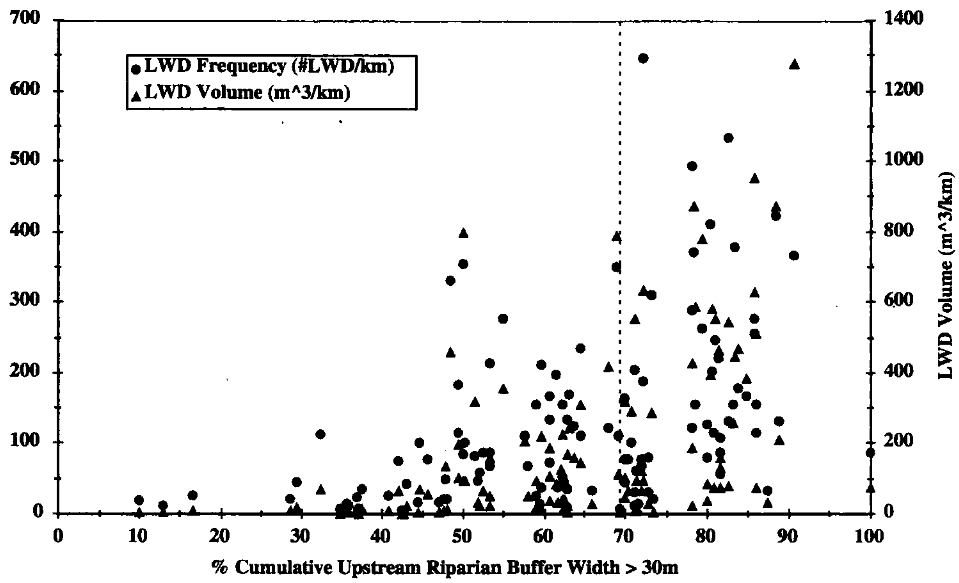


Figure 9. LWD quantity and riparian integrity in Puget Sound lowland (PSL) streams.

The stream bottom substratum is critical habitat for salmonid egg incubation and embryo development, as well as being habitat for benthic macroinvertebrates. Streambed quality can be degraded by deposition of fine sediment, by streambed instability due to high flows, or both. Although the redistribution of streambed particles is a natural process in gravel-bed streams, excessive scour and aggradation often result from excessive flows. Streambed stability was monitored using bead-type scour monitors (Figure 10) installed in salmonid spawning riffles in selected reaches (Nawa and Frissell, 1993).

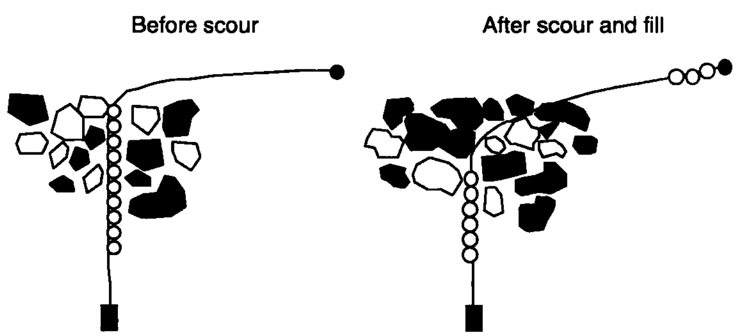


Figure 10. Sliding-bead type scour monitors.

As would be expected, larger scour and/or fill events usually resulted from larger storms and the resultant higher flows. The available stream power and basal shear stress may be the most significant factors affecting the potential for streambed instability. Stream power is proportional to discharge and slope. Since flows tend to increase with urbanization, it would generally be expected that stream power would increase as urbanization does, all else being equal. Cooper (1996) found this to be the case for the PSL study streams. Shear stress is dependent on slope, flow velocity, and streambed roughness. It is the critical basal shear stress that determines the onset of streambed particle motion and the magnitude of scour and/or aggradation. Because local slope and streambed roughness are highly variable, it is not surprising that scour and fill are also variable and that no significant relationship was noted between the 2-year stormflow to winter-baseflow ratio and any of the scour monitor measurements. This tends to emphasize the local nature of scour and aggradation events. Nevertheless, basin urbanization in PSL streams was found to have the potential to cause locally excessive scour and fill. Urban streams in the PSL with gradients greater than 2% and lacking in LWD were found to be more susceptible to scour than their undeveloped counterparts.

Streambank erosion was also far more common in PSL streams draining urbanized watersheds than in streams draining undeveloped watersheds. A survey protocol similar to that of Booth (1996) was used to evaluate all stream segments for streambank stability. Stream segments where >75% of the reach was classified as stable were given a score of 4. Between 50% and 75% was scored as 3, 25–50% as 2, and <25% as 1. Artificial streambank protection (riprap) was considered a sign of bank instability and scored as 1. Only two undeveloped, reference stream segments (TIA < 5%) had a stability rating of less than 3. In the 5–10% range, the streambank ratings were generally 3 or 4. Between 10% and 30%, there was a fairly even mixture of streambank conditions from stable and natural to highly eroded or artificially "protected." Where the TIA was greater than 30%, no segments had a streambank stability rating of 4, and very few had a rating of 3. The latter were found only in segments with intact and wide riparian corridors. Artificial streambank protection (riprap) was a common feature of all highly urbanized streams (TIA > 45%). Overall, the streambank stability rating was inversely correlated with cumulative development (%TIA) upstream and even more closely correlated with development within the segment itself, perhaps reflecting the local effects of construction and other human activities. Streambank stability was also influenced by the condition of the riparian vegetation surrounding the stream. In this study, the streambank stability rating was strongly related to the width of the riparian buffer zone and inversely related to the number of breaks in the riparian corridor. While not completely responsible for the level of streambank erosion, basin urbanization and loss of riparian vegetation contribute to the instability of stream banks. Besides vegetative cover, other stream corridor characteristics, such as soil type and valley hillslope gradient, also contribute to the stability of the stream banks.

Fine sediment sampling (using the McNeil method) indicated that urbanization can also degrade streambed habitat. The levels of fine sediment (% fines) were related to upstream urban development, but the variability, even in undeveloped reaches, was quite high (Wydzga, 1997). Nevertheless, fines did not exceed 15% until TIA exceeded 20%. In the highly urbanized basins (TIA > 45%), the fine sediment was consistently > 20% except in higher gradient reaches, where the sediment was presumably flushed by high storm flows.

The intragravel dissolved oxygen (IGDO) was also monitored as an integrative measure of the deleterious effect of fine sediment on salmonid incubating habitat. IGDO monitors were installed in artificial salmonid redds and monitored throughout the coho incubation period (Figure 11). A significant impact of fine sediment on salmonids is the degradation of spawning and incubating habitat (Chapman, 1988). The incubation period represents a critical and sensitive phase of the salmonid life cycle. During this period, the typical mortality rate in natural streams can be quite high (>75%). A high percentage of fine sediment can effectively clog the interstitial spaces of the substrata and reduce water flow to the intragravel region. This can reduce the levels of IGDO and build up metabolic wastes, leading to even higher mortality. In extreme situations, sediment can form a barrier to alevin emergence, resulting in entombment and death. Elevated fine sediment levels can also have

various sublethal effects on developing salmonids which may reduce the odds of survival in later life stages (Steward, 1983). While low IGDO levels are typically associated with fine sediment intrusion into the salmonid redd, local conditions can have a strong influence on intragravel conditions as well as the distribution of fine sediment (Chapman, 1988). Spawning salmonids themselves can also reduce the fine sediment content of the substrata, at least temporarily.

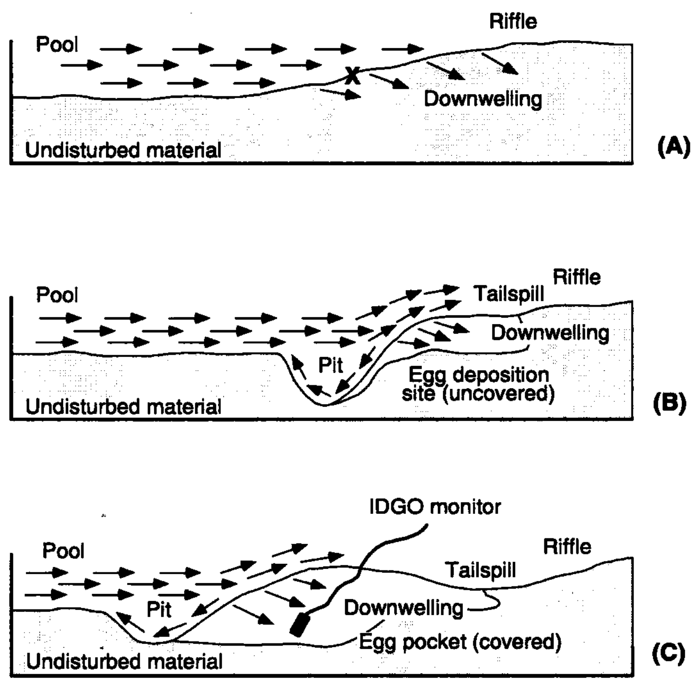


Figure 11. Architecture of a typical salmonid redd showing position of intragravel dissolved oxygen (IGDO) monitor (c). (a) Streambed topography near pool tailout. Likely spawning area (area of flow into gravel) is marked with an X. (b) Redd construction creates a low-flow zone, facilitating egg deposition and fertilization (fine sediment is flushed from pocket). (c) egg pocket covered by upstream digging and down-welling flow maximized by redd topography. Induced flow flushes sediment, provides oxygenated surface water to developing embryos, and removes metabolic wastes. (modified from Bjorn and Reiser, 1991).

Coincident measurements of instream DO and IGDO allowed calculation of a IGDO/DO interchange ratio (Figure 12). In all but one case, the mean interchange ratio was > 80% in the undeveloped reaches (TIA < 5%). As basin development (%TIA) increased above 10%, there was a great majority of the reaches in which the mean interchange ratio was well below 80% (as low as 30%). While these DO levels are not lethal, low IGDO levels during embryo development can reduce survival to emergence (Chapman, 1988). Several urbanized stream segments had unexpectedly high (>80%) IGDO concentrations (see Figure 12). All of these segments were associated with intact riparian corridors and upstream riparian wetlands. Generally, these reaches also had stable stream banks and adequate levels of instream LWD.

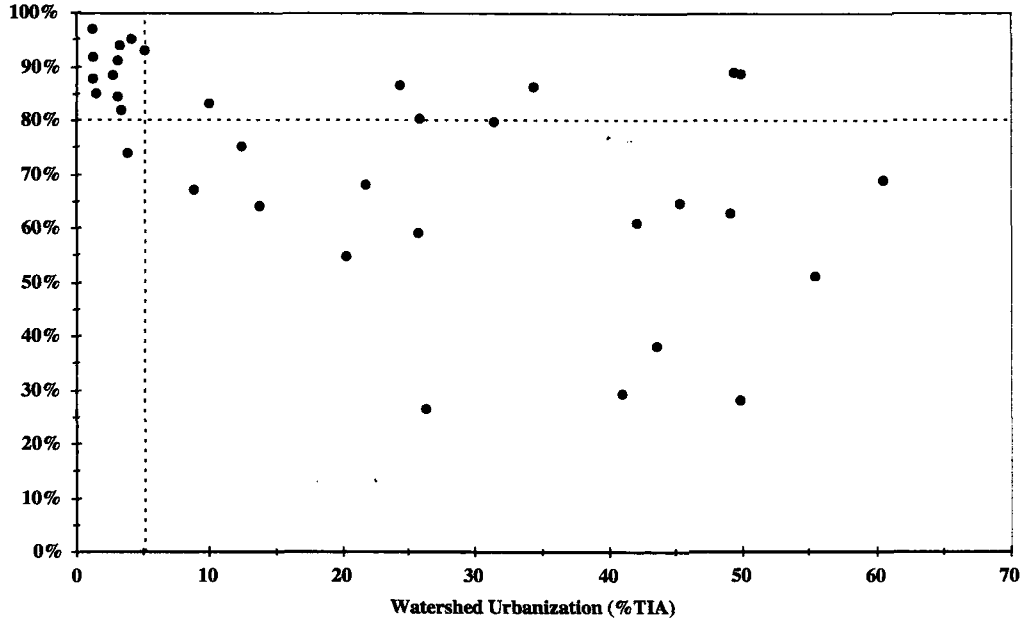


Figure 12. Relationship between urbanization (%TIA) and the ratio between mean intragravel dissolved oxygen (IGDO) and instream dissolved oxygen (DO) in Puget Sound lowland (PSL) streams.

Coho salmon rely heavily on small lowland streams and associated off-channel wetland areas during their rearing phase (Bisson et al., 1988). They are the only species of salmon that overwinters in the small streams of the PSL. Cutthroat trout are commonly found in almost all small streams in the PNW. Cutthroat and coho are sympatric in many small streams in the PNW and as such are potential competitors (adult cutthroat also prey on juvenile coho). In general, habitat, rather than food, is the limiting resource for most salmonids in the PNW region (Groot and Margolis, 1991). In urban streams of the PSL, rearing habitat appears to be the limiting factor. This study found that in all but the most pristine lowland streams (TIA < 5%) significantly less than 50% of the stream habitat area was pools (Figure 13). Even in these "reference" streams, pool habitat was generally below the "target" level of 50% recommended (Peterson et al., 1992). This is presumably due to the effects of past land-use practices (timber harvest and agriculture) and lack of instream LWD (see Figures 8 and 9). In addition, the fraction of cover on pools decreased in proportion to sub-basin development. The most urbanized streams had significantly less pool habitat (on average, less than half) than that found in reference streams (Figure 13a). Coho rear primarily in pools with high habitat complexity, with abundant cover, and where LWD is the main structural component (Bisson et al., 1988). The cumulative effects of human activity in the watershed, including the loss of riparian forest area and reduced instream LWD, significantly reduced pool area, pool diversity, and pool quality. As a result, instream habitat complexity in urban streams is far below that necessary to support a diverse and abundant salmonid community.

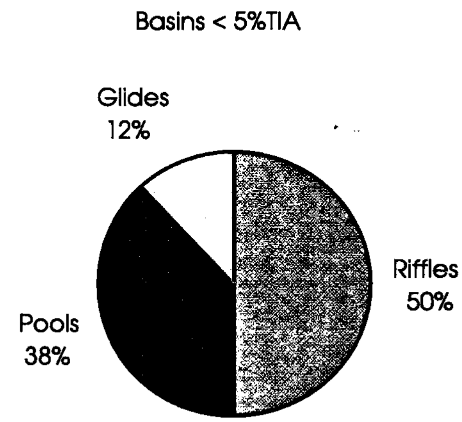


Figure 13a. Habitat unit distribution (TIA < 5%).

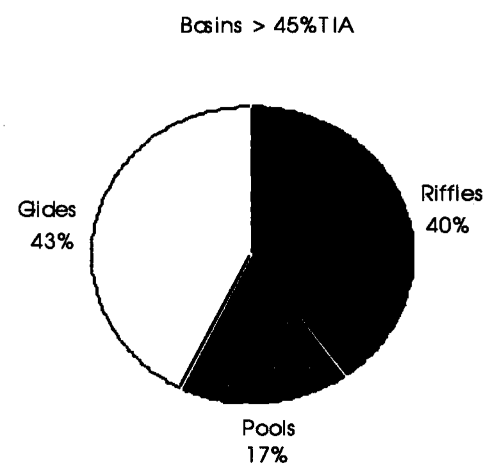


Figure 13b. Habitat unit distribution (TIA > 45%).

Biological Integrity

The multi-metric benthic index of biotic integrity (B-IBI) developed by Kleindl (1995) and Karr (1991) was used as a measure of the biological condition of the benthic macroinvertebrate community in PSL streams. The abundance ratio of juvenile coho salmon to cutthroat trout (Lucchetti and Fuerstenberg, 1993) was used as a measure of salmonid community integrity. Figure 14 shows a direct relationship between urbanization (%TIA) and biological integrity, using both measures. Only undeveloped reaches (TIA < 5%) exhibited an B-IBI of 32 or greater (45 is the maximum possible score). There also appears to be a rapid decline in biological integrity with the onset of urbanization. At the same time, it appears unlikely that streams draining highly urbanized sub-basins (TIA > 45%) could maintain a B-IBI greater than 15 (the minimum B-IBI is 9). B-IBI scores between 25 and 32 were associated with reaches with a TIA < 10%, with eight notable exceptions (see Figure 14). These eight reaches had sub-basin TIA values in the 25%–35% (suburban) range, and yet each had a much higher biological integrity than other streams at this level of development. All eight had a large upstream fraction of intact riparian wetlands and all but one had a large upstream fraction of wide riparian buffer (>70% of the stream corridor with a buffer width > 30 m). These observations indicate that maintenance of a wide, natural riparian corridor may mitigate some of the effects of watershed urbanization.

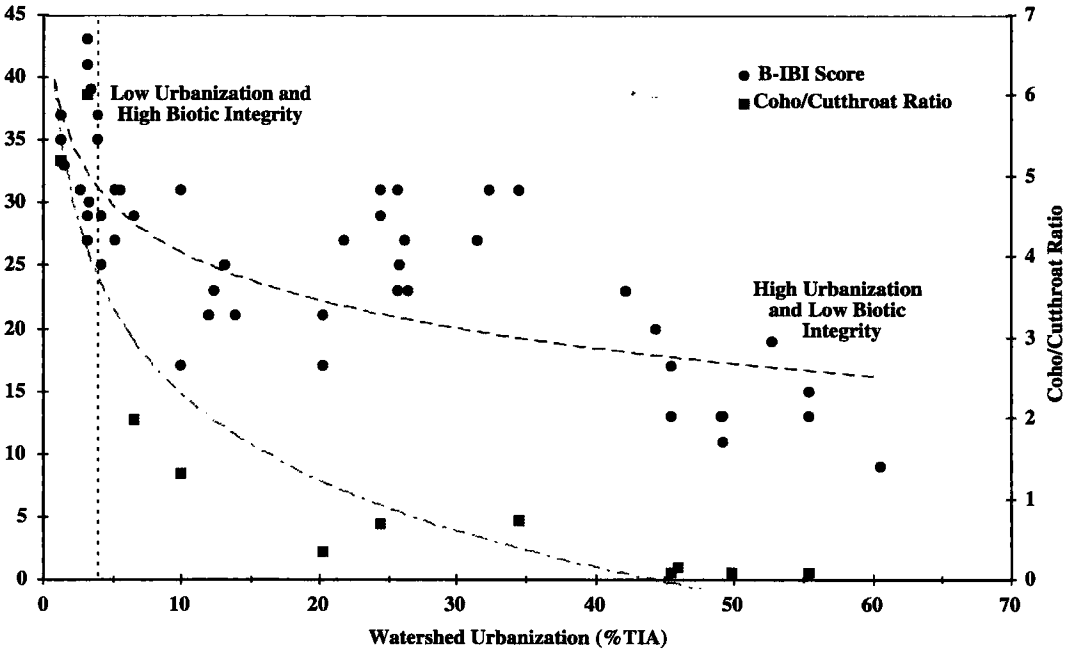


Figure 14. Relationship between watershed urbanization (%TIA) and biological integrity in Puget Sound lowland (PSL) streams. The benthic index of biotic integrity (B-IBI) and the abundance ratio of juvenile coho salmon to cutthroat trout were used as indices of biological integrity.

Urbanization also appears to alter the relationship between juvenile coho salmon and cutthroat trout. In this study, coho tended to dominate in undeveloped (TIA < 5%) streams, whereas cutthroat were more tolerant of conditions found in urbanized streams. Figure 14 shows the coho-to-cutthroat abundance ratio in those PSL study streams (11) where data were available for the period of the study. Natural coho dominance (cutthroat:coho ratio > 2) was seen only at very low watershed development levels (TIA < 5%). It is significant that both salmonid and macroinvertebrate data indicate a substantial loss of biological integrity at a very low level of urbanization. These results confirmed the findings of earlier regional studies (Perkins, 1982; Steward, 1983; Scott et al., 1986; Lucchetti and Fuerstenberg, 1993).

Given that relationships were identified between basin development and both instream habitat characteristics and biological integrity, it is reasonable to hypothesize that similar direct relationships exist between physical habitat and biological integrity. As a general rule, instream habitat (both quantity and quality) correlated well with biological integrity. For example, measures of spawning and rearing habitat quality were closely related to the coho:cutthroat ratio, and measures of streambed quality (benthic macroinvertebrates) were closely related to the B-IBI. Chemical water quality may also influence aquatic biota at higher levels of watershed urbanization.

In addition to the quantitative habitat measures, a multi-metric Qualitative Habitat Index (QHI) was also developed for PSL streams. This index assigns scores of poor (1), fair (2), good (3), and excellent (4) to each of 15 habitat-related metrics, then sums all 15 metrics for a final reach-level score (the minimum score is 15 and maximum is 60). The QHI is similar in design to that used in Ohio (Rankin, 1989) and as part of the US EPA Rapid Bioassessment Protocol (Plafkin et al., 1989). As was expected, biological integrity was directly proportional to instream habitat quality (Figure 15). Coho dominance is consistent with a B-IBI > 33 and a QHI > 47, conditions found only in natural (TIA < 5%), undeveloped streams. These results were consistent with the findings of a similar

study in Delaware (Maxted et al., 1994). The QHI has the advantage of being simpler (less costly) than more quantitative survey protocols, but may not meet the often rigorous (quantitative) requirements of resource managers. However, as a screening tool, it certainly has merit.

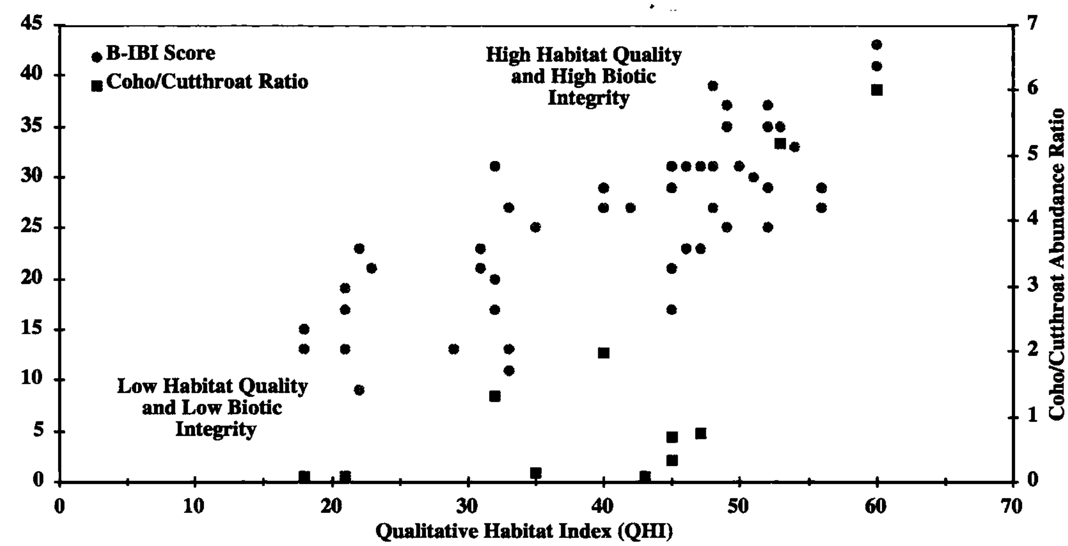


Figure 15. Relationship between instream habitat quality and biotic integrity in Puget Sound lowland (PSL) streams. The benthic index of biotic integrity (B-IBI) and the ratio of juvenile coho salmon to cutthroat trout are used as indices of biological integrity.

A major finding of this study was that wide, continuous, and mature-forested riparian corridors appear to be effective in mitigating at least some of the cumulative effects of adjacent development. Figure 16 illustrates how the combination of riparian buffer condition and basin imperviousness affects biological integrity, as measured by the B-IBI. These observations suggest a set of possible stream quality zones similar to those proposed by Steedman (1988). Excellent (natural) stream quality requires a low level of watershed development and a substantial amount of intact, high-quality riparian corridor. If a "good" or "fair" stream quality is acceptable, then greater development may be possible, with an increasing amount of protected riparian buffer being required. Poor stream quality is almost guaranteed in highly urbanized watersheds or where riparian corridors are negatively impacted by human activities such as development, timber harvest, grazing, or agriculture. Because of the mixture of historical development practices and resource protection strategies included in the study area, it was difficult to make an exact judgment as to how much riparian corridor is appropriate for each specific development scenario. More intensive research is needed in this area.

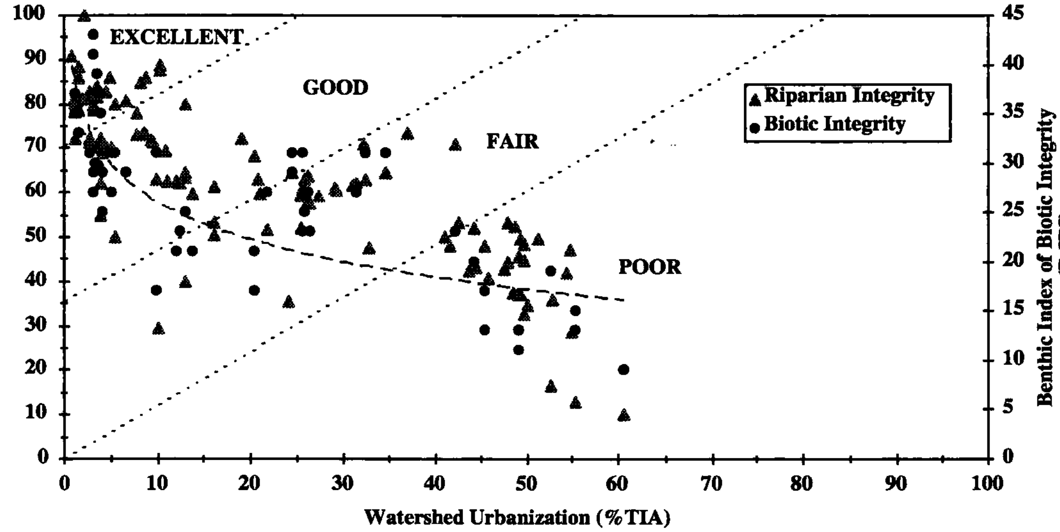


Figure 16. Relationship between basin development, riparian buffer width, and biological integrity in PSL streams.

Summary

Results of the PSL stream study have shown that the physical, chemical, and biological characteristics of streams change with increasing urbanization in a continuous rather than a threshold fashion. Although the patterns of change differed among the attributes studied and were more strongly evident for some than for others, physical and biological measures generally changed most rapidly during the initial phase of the urbanization process as TIA rose above 5–10%. As urbanization progressed, the rate of degradation of habitat and biologic integrity usually became more constant. There was also direct evidence that alteration of the watershed hydrologic regime was the leading cause for the overall changes observed in instream habitat conditions.

Chemical water quality constituents and concentrations of metals in sediments did not follow this pattern. These variables changed little over the urbanization gradient until imperviousness (%TIA) approached 40%. Even then water column concentrations did not surpass aquatic life criteria, and sediment concentrations remained far below freshwater sediment guidelines. As urbanization (%TIA) increases above the 50% level, the point where most pollutant concentrations rise rapidly, it is likely that the role of water and sediment chemical water quality constituents becomes more important biologically.

It is also apparent that, for almost all PSL streams, the quantity and quality of large woody debris must be restored for natural instream habitat diversity and complexity to be realized. Of course, prior to undertaking any habitat enhancement or rehabilitation efforts, the basin hydrologic regime must be restored to nearly natural conditions. Results suggest that resource managers should concentrate on preserving high-quality stream systems through land-use controls, maintenance of riparian buffers, and protection of critical habitat. Enhancement and mitigation efforts should be focused on watersheds where ecological function is impaired but not entirely lost.

Alterations in the biological community of urban streams are clearly a function of many variables representing conditions in both the immediate and more remote environment. In addition to urbanization level, a key determinant of biological integrity appears to be the quantity and quality of the riparian zone available to buffer the stream ecosystem, in some measure, from negative influences in the watershed (see Figure 16). Instream habitat conditions also had a significant influence on instream biota. Streambed quality, including fine sediment content and streambed

stability, clearly affected the benthic macroinvertebrate community (as measured by the B-IBI). The composition of the salmonid community was also influenced by a variety of instream physio-chemical attributes. In the PSL region, management of all streams for coho (and other sensitive salmonid species) may not be feasible. Management for cutthroat trout may be a more viable alternative for streams draining more highly urbanized watersheds. The apparent link shown here between watershed, riparian zone, instream habitat, and biota supports management of aquatic systems on a watershed scale.

This research indicates that there is a set of conditions that, though not individually sufficient, are necessary to maintain a high level of stream quality or ecological integrity (physical, chemical, and biological). If maintenance of that high level is the goal, then this set of conditions constitutes the standards that must be achieved if the goal is to be met. For the PSL streams, imperviousness must be severely limited, unless mitigated by extensive protection of the riparian corridor and BMPs. Downstream changes to both the form and function of stream systems appear to be inevitable unless limits are placed on the extent of urban development. Stream ecosystems are not governed by a set of absolute parameters but are dynamic and complex systems. We cannot "manage" streams but instead should work more as "stewards" to maintain naturally high stream quality. Preservation and protection of high-quality resources should be a priority. Engineering solutions are useful in some situations in urban streams, but in most cases they cannot fully mitigate the effects of development. Rehabilitation and enhancement of aquatic resources will almost certainly be required in all but the most pristine watersheds. In order to support natural levels of stream quality, the following recommendations are proposed.

- Reduce watershed imperviousness, especially targeting transportation-related surfaces and compacted pervious areas.
- Preserve at least 50% of the total watershed surface area as natural forest cover.
- Maintain an urbanized stream system drainage density that is within 25% of pre-development conditions (i.e., an urban/natural DD ratio < 1.25).
- Continuously monitor stream flow and maintain 2-year stormflow/baseflow discharge ratio of much less than 20.
- Allow no storm water to drain directly into a stream without first being treated by quality and quantity control facilities.
- Replace culverted road crossings with bridges or by arched culverts with natural streambed material.
- Retrofit existing BMPs or replace them with regional (sub-basin) stormwater control facilities with the goal of restoring the natural hydrologic regime.
- Limit stream crossings by roads or utility lines to less than two per kilometer of stream length and strive to maintain a nearly continuous riparian corridor.
- Ensure that at least 70% of the riparian corridor has a minimum buffer width of 30 m and utilize wider (100-m) buffers around more sensitive or valuable resource areas.
- Limit encroachment of the riparian buffer zone through education and enforcement (< 10% of the riparian corridor should be allowed to have a buffer width of < 10 m).
- Actively manage the riparian zone to ensure a long-range goal of maintaining at least 60% of the corridor as mature, coniferous forest.
- Allow no development in the active (100-year) floodplain area of streams. Allow the stream channel freedom of movement within the floodplain area.
- Protect and enhance headwater wetlands and off-channel riparian wetland areas as natural stormwater storage areas and valuable aquatic habitat resources (buffers).

- Adopt a set of regionally specific stream assessment protocols including standardized biological sampling (e.g., B-IBI).
- Under low-to-moderate basin development, use chemical water quality monitoring sparingly, i.e., only if a chemical pollutant is suspected or in situations where biological monitoring indicates a problem. For highly urbanized streams, sampling should be more frequent but should still be focused on specific constituents of concern.
- Taylor monitoring of instream physical conditions to the specific situation. Salmonid habitat surveys should include a measure of rearing habitat (LWD and/or pools) and a measure of spawning/incubating habitat (%fines and/or IGDO). In addition, standard channel morphological characteristics (pebble count, streambank condition) should be measured. Scour monitoring should be used to evaluate local streambed stability in association with specific development activity.

The complexity and diversity of salmonid life cycles and stream communities, along with our limited understanding of them, should engender caution in proposing any simple solutions to reverse the cumulative effects of urbanization in streams of the PSL region as well as other regions.

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Treatment Wetlands—What Happened in Black Diamond

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Introduction

Several west coast communities are using or proposing to use treatment wetlands for municipal wastewater (sewage) treatment to improve effluent quality and to restore or enhance wildlife habitat.

This paper reviews the development history of treatment wetlands in Black Diamond, Washington, and five communities in Oregon and Northern California. The systems profiled here include the municipal wetland treatment systems in the region whose development history is notable, usually from a standpoint of regulatory compliance, and for whom a database exists to show how well the system works. The available information suggests that Black Diamond is unique in the use of an unimproved natural wetland; that Arcata is a success in part as a result of the application of beneficial use standards and watershed location; that well-designed and constructed first generation wetlands perform well with respect to the water quality parameters for which they are designed (biochemical oxygen demand and total suspended solids) and that the habitat created by municipal treatment wetlands is regionally significant, possibly replacing wetland functions and values of wetlands lost to development.

Black Diamond, Washington

Black Diamond is a town of approximately 1600 located at the base of the Cascade Range in western Washington, 30 miles southeast of Seattle. Until the early 1980s, the residents of Black Diamond were served by on-site and community septic systems (Thielen, 1978).

In 1979, Black Diamond adopted a wastewater facilities plan to construct an aerated lagoon and a "marsh-lagoon" to treat community wastewater. The marsh-lagoon, when constructed, would consist of two 3.5-acre, 4-foot deep lagoons sited within an existing 130-acre marsh. Nutrient removal, necessary for compliance with proposed permit conditions, would be achieved in part through an annual harvest of marsh-lagoon vegetation. Marsh-lagoon effluent would be discharged to the surrounding wetland, which is traversed by Rock Creek upstream of Lake Sawyer (Kramer, Chin and Mayo, 1979 and 1980).

Construction in the existing wetland required a US Army Corps of Engineers permit. During the permitting process, United States Environmental Protection Agency (EPA) wetlands staff, other resource agency staff, and environmental organizations objected to the siting of a treatment facility in an existing wetland. Agency staff recommended that the city limit wetland improvements to installation of a weir at a downstream location to increase detention time and treatment, or that the city use an alternative wetland, one that was being invaded by trees and which was, as a result, losing marsh characteristics (Kramer, Chin and Mayo, 1980).

The town was apparently surprised by these objections, believing that EPA and the Washington State Department of Ecology (Ecology) had approved the use of the wetland with the approval of the facilities plan.

In response to these comments, Black Diamond prepared a facilities plan addendum that evaluated the proposed marsh-lagoon and, alternatively, use of the 130-acre marsh in its natural state. The study concluded that both systems could meet nutrient effluent limits but that a decrease in phosphorus reductions could be expected during the 20-year life of the project. The study recommended use of the natural wetland. Advantages of using the natural wetland included lower construction-related environmental impacts and a savings of several hundred thousand dollars in

construction costs. The town also avoided the Corps permitting process under this alternative (Kramer, Chin and Mayo, 1980; Stephens, 1986).

The treatment system, an aerated lagoon with natural marsh treatment, qualified for 100% funding from EPA under Innovative and Alternative funding criteria and began operating in 1981. Shortly thereafter, algal blooms were reported in Lake Sawyer (Peterson, 1990).

In 1985, after several years of treatment plant operation and reports of increased algae in Lake Sawyer, a consultant was hired to evaluate the performance of the Black Diamond facility. The consultant concluded that the system was not meeting mass removal performance requirements for biochemical oxygen demand (BOD), total suspended solids (TSS), and phosphorus. Samples taken in May, 1985, showed approximately 70% BOD removal, whereas the town's discharge permit specified 85% removal. Inorganic nitrogen was reduced by 85%, compared to the seasonal removal requirement of 70% . Total nitrogen was reduced by 55%. Phosphorus concentrations in Rock Creek were reported to be ten times that of pre-discharge concentrations. The study noted that surface and/or groundwater flow into the marsh provided 50-fold dilution of the influent and was partially responsible for decreases in pollutant concentrations (R.W. Beck and Associates, 1985).

EPA was approached to fund system improvements when it became apparent that Black Diamond was not meeting permit limits. EPA staff were initially concerned with the amount of data available to support a finding of failure—a finding necessary for EPA to fund improvements under existing effluent limits. EPA could also fund improvements if the parties agreed that more stringent limits were needed based upon receiving water sensitivity. However, EPA suggested that more stringent limits could be prescribed only if supported by an evaluation of all pollution sources to Lake Sawyer (Catey, 1986; Joy, 1987; Saikewicz, 1988; Williams, 1989).

The location and possible dearth of monitoring stations may have created difficulty in evaluating the performance of the Black Diamond wetland. Shortly after the system went on-line, the effluent sampling point was established in Rock Creek downstream of the wetland. Water quality at this station would be affected by upstream watershed influences. The choice of this location as a sampling point may reflect the integrated nature of Rock Creek and the wetland—that is, it may have been difficult or impossible to find a discrete location defining the wetland discharge into the creek. Additionally, several unmonitored creeks and springs fed the wetland.

In 1988, despite EPA's previous recommendation for a watershed-based analysis, Ecology proposed more restrictive effluent limits for Black Diamond. The following year, a consultant to Black Diamond summarized alternatives available to meet the new limits and recommended abandonment of the lagoon/marsh system in favor of conveyance to a regional treatment facility (Brown and Caldwell, 1989).

In 1991, Ecology published the results of a year long study of Lake Sawyer. The report described the condition of Lake Sawyer as mesotrophic with an 18% expectation of attaining eutrophic conditions. The report concluded that the Black Diamond wastewater treatment facility accounted for 40% of the lake's external phosphorous load and that removal of the discharge from the creek would decrease the likelihood of eventual eutrophication. The report noted that development in the Rock Creek watershed had also contributed to deteriorating water quality in Rock Creek and recommended management practices for the control of phosphorus from future development (Carroll and Pelletier, 1991).

The diagnostic study also reported that the lagoon and wetland treatment system removed roughly 77% of the phosphorus and 73% of the nitrogen from Black Diamond's waste stream. The report noted that these reductions surpassed original design expectations.

Even before publication of the 1991 Ecology study, EPA was apparently satisfied with the accumulation of data and experience at Black Diamond. The agency adopted a finding of failure and funded a connection to the regional wastewater collection system. Black Diamond's wastewater is now treated at the regional facility in Renton.

Wetland influent and effluent data from Black Diamond for 1990 and 1992, two of the last three years of operation, are presented in the Discussion section.

Cannon Beach, Oregon

Cannon Beach is located 100 miles west of Portland, Oregon. Since 1984, this coastal community of 1300 has treated its wastewater using aerated and facultative lagoons and a 15-acre modified natural free-water-surface treatment wetland. Planning for the treatment system occurred over a period of years and generated some local controversy.

In the 1970s, summer flows to the existing wastewater treatment plant exceeded permit effluent limits and the design capacity of the plant. In response to these conditions, Cannon Beach prepared an updated facilities plan and supplement in 1976 and 1977. However, the Cannon Beach Sewer Advisory Board saw "no justification in backing a conventional collection and treatment approach...," and recommended that the City Council explore alternative technologies instead (Cannon Beach Sewer Advisory Board, 1980).

The town, with considerable citizen involvement, eventually proposed a system that included a treatment marsh and previously recommended lagoon upgrades to meet summer seasonal limits on BOD and TSS (10/10 mg/L). Like Black Diamond, Cannon Beach recommended use of and improvements to a local natural wetland. Berms would be placed around the wetland to improve detention and redwood baffles would be placed in the wetland to prevent flow short-circuiting (Kramer, Chin, & Mayo, 1978).

Both the Oregon Department of Fish and Wildlife and the United States Fish and Wildlife Service objected to the use of a natural wetland for wastewater treatment.

In response to agency concerns, the city contracted for a biological evaluation of the wetland. The evaluation noted that the proposed 15-acre wetland treatment area included five different plant communities, four of which were forested, and that the wetland was used by a number of wildlife species, including Roosevelt elk, beaver, mallards, canvasbacks, great blue herons, kingfishers, and pileated woodpeckers. The report noted, however, that the site was part of a larger, 150-acre wetland, suggesting that previous fears of losing a unique wetland were possibly unfounded, and that the site was originally much drier. The site had developed wetland characteristics as a result of logging and changes in site drainage accompanying development (Kramer, Chin, & Mayo, 1981).

As a result of the biological evaluation, the city proposed a modified design that minimized fencing to allow continued wildlife access and used planted earthen baffles instead of redwood baffles. The biological information and proposed modifications apparently satisfied resource agency concerns. The modified plan was adopted by the Cannon Beach City Council, approved by the Oregon Department of Environmental Quality, and funded by EPA as an Innovative and Alternative project. The treatment system began operating in 1984. The wetland is used only for summer flows. Discharge is to Ecola Creek, about one-half mile above the mouth of the creek at the Pacific Ocean (US EPA, 1993; Oregon State Department of Environmental Quality, 1993). Wetland data are presented in the Discussion section.

Unified Sewerage Agency (Hillsboro, Oregon)

The Unified Sewerage Agency (USA) serves an urbanizing area in Washington County in the northern Willamette River valley in the state of Oregon. USA operates four wastewater treatment plants with a combined flow of approximately forty million gallons per day (40 mgd). These plants discharge to the Tualitin River during winter months and to reclamation facilities, including the 15-acre Jackson Bottoms Experimental Wetland (JBEW), between April and October. Development of reclamation facilities was spurred in part by the settlement of two lawsuits by the Portland-based Northwest Environmental Defense Center. One suit, related to promulgation of TMDLs for phosphorus for 11 Oregon streams, including the Tualitin, was settled in 1988; a second, related to

alleged violations of permit conditions by USA, was settled in 1989. The JBEW, in use since 1989, treats secondary effluent discharged from the two mgd Hillsboro wastewater treatment plant (Unified Sewerage Agency, 1990).

The JBEW was developed to investigate the use of a treatment wetland to remove nutrients from wastewater and to investigate the use of wastewater to enhance biodiversity in a wetland dominated by reed canary grass (*Phalaris arundinacea*). The treatment wetland is a constructed free-water-surface wetland developed out of an existing wetland. The wetland is comprised of 17 cells underlain by three soil types. Shallow areas (1 ft. depth) are planted with *Typha* and transition to deeper areas (3 ft. depth) planted with sago pondweed (*Potamogeton pectinaturs*) (Geiger et al., 1993; Scientific Resources and Luzier Hydrosciences, 1990). The wetland is located within the 434-acre Jackson Bottoms Wetland Preserve, owned by USA and the City of Hillsboro and managed in accordance with a Natural Resource Management Plan and permits issued by the Oregon Division of State Lands and the US Army Corps of Engineers. In 1992, approximately 474 million gallons of effluent were distributed to 350 acres of land within the Preserve.

Treatment at JBEW is complicated by site hydrology and topography, and possibly by initial construction practices. The wetland was originally planned as a single, sinuous, flow-through system. However, the pre-construction survey suggested that flat site conditions would preclude such a design and wetland cells were built instead. Subsequently, after the third year of operation, USA staff reported that some flow thought to discharge to groundwater discharged instead through berms into adjacent drainage ditches. Consultants estimated that 20% of inflows discharged to groundwater through wetland soils, and 30% of inflows discharge through side berms to the local drainage system, and that short-circuiting could be the result of poor initial construction practices (Scientific Resources et. al., 1995).

Reed canary grass continued to thrive and even increased in extent over the initial 3-year monitoring period. Previously, researchers at the site had not observed the grass growing in conditions of continuous flooding. Although reed canary grass is not a preferred species, the wetland evidently provides nesting habitat for a number of avian species (Willis, personal communication). Wetland data are presented in the Discussion section.

Mt. View Sanitary District (Martinez, California)

The Mt. View Sanitary District serves a community of 16,000 living in and around the City of Martinez, California, in the San Francisco Bay Area. The District operates a 1.3 mgd advanced secondary treatment plant that discharges to a 21-acre constructed, free-water-surface wetland. Treatment wetlands and recent plant upgrades to protect wetland habitat were developed as a result of an evolving regional regulatory policy.

In 1969, when the District upgraded to secondary treatment, it decided to continue its discharge to Peyton Slough rather than construct a force main to, and a new outfall in, the Carquinez Straights within the Sacramento River/San Francisco Bay Estuary. Subsequently, in 1971, the San Francisco Bay Regional Water Quality Control Board (RWQCB) adopted a basin plan which prohibited discharges to receiving waters that provided less than 10:1 dilution, including Peyton Slough. The plan allowed for exemptions when the discharger could show that the discharge resulted in a "net environmental benefit."

In 1974, the District constructed a nine-acre freshwater marsh, redirected part of its discharge to that marsh, and started a three-year pilot study to demonstrate compliance with the new regional policy.

At about the time the District was completing its pilot study, in 1977, the RWQCB adopted a policy that stipulated that marshes created under the net environmental benefit exemption were to be protected as receiving waters. As a result, Mt. View is required to meet effluent limits for its discharge to the constructed wetland, rather than for the discharge from the wetland to Peyton slough.

The Mt. View Sanitary District has pursued two courses of action over the past twenty years to comply with regulatory agency policy regarding net environmental benefit. First, the District

expanded its created freshwater marsh to 21 acres in 1977 and later purchased 65 acres of adjacent brackish marsh immediately downstream. Second, between 1992 and 1995, the District completed treatment plant upgrades that reduced the discharge of ammonia to the marsh and replaced chlorine-based disinfection with filtration and ultra-violet light (Wilson, personal communication).

Even before treatment plant upgrades, the created wetland provided significant regional habitat within the industrializing I-680 highway corridor. By 1986, district biologists have documented over 100 species of birds using the wetland area. Observations have been made on 58 species of wading birds and waterfowl, seven species of raptors, and ten species of gulls and terns. An assemblage of invertebrates, fish, amphibians, and reptiles also uses the wetland, including the western pond turtle (*Clemmys marmorata*) (Bogaert and Fish, 1986). The western pond turtle is an endangered species in Washington State and a federal species of concern.

Wetland data are presented in the Discussion section.

Arcata, California

The City of Arcata is a community of 19,000 located on California's northwest coast, 100 miles south of the Oregon border. The city is served by a 2.3 mgd wastewater treatment facility comprised of primary clarifiers, oxidation ponds, 7.5 acres of treatment wetlands, and 31 acres of treatment/enhancement wetlands. Discharge is to Humboldt Bay. The City developed the treatment system in the late 1970s and early-to-mid 1980s amidst considerable local controversy and as a result of changes in state regulatory policy.

In 1974, the State Water Resources Control Board adopted the "Bays and Estuaries Policy" prohibiting discharges into California's shallow bays and estuaries, including Humboldt Bay, unless the discharger could show that the discharge enhanced the "beneficial uses" of the receiving water. After some research, the city concluded that a marsh treatment system would enhance the beneficial uses of Humboldt Bay. Those uses include, among others, recreation (water-contact and non-water contact), wildlife habitat, preservation of rare and endangered species, marine habitat, fish migration, fish spawning, and shellfish harvesting.

In 1979, the city applied for and received funds from the California State Coastal Conservancy to acquire and develop former marsh lands adjacent to the wastewater treatment plant for wetland habitat restoration, public access, and the beneficial use of wastewater for marsh enhancement. The city completed restoration work on these enhancement marshes in July, 1981 (Mangelsdorf, 1993).[1]

Simultaneously, the City entered into negotiations with state regulatory officials. The City requested that the state approve funding for a pilot project to investigate the use of treatment wetlands to enhance the beneficial uses, including wildlife habitat, of Humboldt Bay. Initially, state regulatory agencies resisted City overtures. As a result, local political leaders introduced legislation at the state level to exempt Arcata from the Bays and Estuaries Policy and allow it to continue discharging directly to Humboldt Bay. According to Mangelsdorf, the legislation "...was heard before the Assembly Committee on Water, Parks and Wildlife and when the State (Water Resources Control Board) Chairman was unable to define the term 'enhancement' for the Assembly Committee, the Committee immediately passed the bill."

Shortly thereafter, the State Water Board reversed a previous position and adopted a resolution authorizing the City to proceed with pilot studies.

The state approved Arcata's wetlands treatment plan after a three-year pilot project. Arcata completed treatment plant upgrades and redirected discharges from the treatment plant to its enhancement wetlands in 1986. Additional treatment marshes were added in 1989. The Arcata City Council has designated the enhancement marshes and surrounding open space the Arcata Marsh and Wildlife Sanctuary (AMWS).

The enhancement marshes are unique from a regulatory standpoint in that the marshes are apparently both regulated waters of the state and an element of the City's wastewater treatment facility. As described in the City's NPDES permit, the enhancement wetlands are regulated as "...waters of the state and the United States...":

> The treatment plant is designed to discharge disinfected wastewater treated to secondary standards to waters of the State and the United States at two locations. Outfall 001 discharges directly to Humboldt Bay. Outfall 002 discharges to the Arcata Marsh (and) Wildlife Sanctuary which consists of 30 acres of freshwater wetland.

The NPDES permit states elsewhere that,

> Continued discharge to Humboldt Bay and compliance with the Bays and Estuaries Policy was achieved by the inclusion of the Arcata Marsh (and) Wildlife Sanctuary as part of the treatment and discharge facility.

As with the Mt. View Sanitary District, effluent limits are set for discharges to the AMWS, but these limits (30/30 for BOD/TSS) are not reflective of effluent limits that could be required for a discharge into a wetland.

Arcata's discharge is based upon a continued showing by the City that the discharge is enhancing the beneficial uses of Humboldt Bay. The City has sponsored research to demonstrate compliance with these standards. Gearheart and Higley (1993) review data on wildlife and public use of the 150-acre marsh and wildlife sanctuary. According to these researchers, over 170 species of birds have been observed in the AMWS, with 1.4 million waterbird use-days recorded annually between 1984 and 1986. Nesting species included mallards, cinnamon teal, northern shoveler, pied-billed grebe, killdeer, and black-necked stilt. The area includes five miles of trails and has become "...a major form of low-cost recreation for bird watchers, nature lovers, fishermen, walkers, joggers, boaters, picnickers, meditators, and tourists." The authors report that, "In a 1987 user survey, the most common reasons given for going to AMWS was its value as a human sanctuary and as a place to enjoy the natural setting and ecology of a marsh." The Redwood Audubon Society conducts weekly nature walks at the AMWS and approximately 900 people a year participate.

Wetland data are presented in the following section.

Discussion

Table 1 presents design information on the treatment wetlands profiled in this paper. Table 2 presents influent and effluent data for the wetlands. Acreage data for Black Diamond in Table 1 is qualified as there is uncertainty as to the amount of acreage contributing to treatment given the presence of Rock Creek and the resulting potential for short-circuiting.

The Black Diamond treatment wetland is the only natural treatment wetland of the five profiled (Table 1). In contrast, treatment wetlands at Cannon Beach and USA were developed by modifying existing wetlands. These modifications are designed to improve detention time and limit short-circuiting and thereby produce an improved effluent quality. Arcata and the Mt. View Sanitary District (Mt. View SD) use constructed treatment wetlands, again to create a controlled environment for treatment.

The data from Arcata and Cannon Beach confirm early design principles that, in relatively small areas, well designed and constructed (or modified) wetlands reduce effluent concentrations of BOD and TSS to levels below 20 mg/L. The relatively high BOD concentration in USA effluent is notable given the concentrations reported at the other facilities.

Table 1. Treatment Wetland Design Washington, Oregon, and Northern California Treatment Wetlands.

System	Year	mgd	Acres/mgd	Pre-treatment	Type
Mt. View SD, CA	1974	1.3	16	Secondary	Constructed
MVSD Upgrade[1]	1995			Adv. Sec.	
Bl. Dmd., WA	1981	0.15	870[2]	Primary	Natural
Can. Beach, OR	1984	0.5	30	Secondary	Mod. Nat.[3]
Arcata, CA	1986	2.3	17	Secondary	Constructed
USA, OR	1989	0.7	21	Secondary	Mod. Nat.[3]

1. Nitrification.
2. Contributing treatment area is unclear.
3. Modified Natural Wetland

Table 2. Treatment Wetland Influent and Effluent Data (Influent to Wetland; Effluent from Wetland).

	Flow (*mgd*)			BOD (*mg/L*)			TSS (*mg/L*)			NH_3 (*mg/L*)			$NO_{3/2}$ (*mg/L*)			Total P (*mg/L*)		
	In.	Ef.	Loss	In.	Ef.	Rem.	In.	Ef.	Rem.	In.	Ef.	Rem.	In.	Ef.	Rem.	In.	Ef.	Rem.
Bl. Diamond-1990	0.17	NA		20	NA		25	NA			.65			.64			.37	
Bl. Diamond-1992	0.13	NA		15	NA		54	NA			.78			1.2			1.3	
Cannon Beach-1996[1]	0.5	0.24	45%	47	5	86%	51	2	96%	12	9.2	21%	2.5	4.7	-83%	2.1	1.9	10%
USA-1990[2]	0.5	0.13	73%	40	51	-28%	9	12	-28%	3.2	0.1	97%	6.9	2.2	68%	7.6	4.0	47%
USA-1992	1.0	0.36	66%	41	71	-73%	5	16	-232%	15	6.4	57%	18	8.2	54%	3.3	3.1	117 %
Mt. View SD-1995	2.0	NA		12	NA		9	NA		1.1	1.0	10%	19	13	30%		NA	
Mt. View SD-1996	2.0	NA		6	NA		8	NA		1.0	0.3	30%	18	14	27%		NA	
Arcata – 1994[3]	2.1	1.5	30%	NA	10		NA	15			NA			NA			NA	
Arcata – 1995	2.7	1.6	40%	NA	14		NA	27			NA			NA			NA	

Data are compiled from NPDES reports, unless otherwise noted. (NA: Not Available).

Some date values are rounded; percentages are based upon original (not rounded) data.

The 1992 data is generally representative of the years 1989-1992.

Between 1990 and 1992, the Hillsboro plant stopped nitrification of wastewater, the result of a 25% increase in wastewater flows, and a service-area-wide ban on phosphorus went into effect. Data are mean values for 17 cells. Data compiled from Scientific Resources et al. (1995) for a three year pilot study.

The 1994 data is generally representative of the year 1992-1994.

On a mass loading basis, pollutant reductions are substantial at most locations, the result of subsurface discharges. None of these wetlands is lined.

These small wetlands are only partially successful in reducing nutrient concentrations. Effluent concentrations of nitrogen are indicative of partial nitrification/denitrification. Nitrogen data from Mt. View SD demonstrates the potential for denitrification. There, nitrification occurs as part of pre-treatment and reduced ammonia discharges probably contribute to increased habitat quality in the wetland.

In general, there has been an explosion of information related to wetlands design since these wetlands were planned and constructed. Recent publications include a comprehensive text (Kadlec and Knight, 1996), updated design manuals (Reed et al., 1995; Water Environment Foundation, 1990), conference proceedings (Hammer, 1988; Moshiri, 1993), and numerous trade journal articles and published papers. Reed and Brown review first generation design methodologies (Reed and Brown, 1992), report on a nation-wide inventory of treatment wetlands (Brown and Reed, 1994), and review experiences with sub-surface flow wetland (Reed and Brown, 1995). The wetlands reviewed here can be classified as first-generation wetlands.

Information developed since these first generation wetlands were built suggests that expanded acreage is needed for nutrient processing, compared to the acreage required for BOD and TSS removal (Hammer and Knight, 1994; Reed et al., 1995; Kadlec and Knight, 1996; Water Environment Foundation, 1990). Additionally, harvest of vegetation for nutrient management is no longer recommended as harvest removes attachment sites for the epiphytic community thought to control nutrient processing (Crites and Tchobanoglous, 1992; Brix, 1994), although some researchers have recommended this practice as recently as 1992 (Rogers et al., 1991; Rogers, 1992). A limited harvest is recommended to preserve open water habitat for *Gambusia* (mosquito fish), a species used in mosquito control programs (Tennessen, 1993; Nolte & Associates, 1996).

Design information also now suggests that phosphorus removal in most wetlands is limited—as it is in most treatment processes (Kadlec and Knight, 1996; Reed et al., 1995). Phosphorus is removed from water during plant growth, but it is returned in the form of plant litter. Phosphorus can be sequestered to some degree in the litter. Phosphorus is also removed via adsorption, complexation, and precipitation in soil during infiltration, but soil phosphorous storage capacity is finite. In areas where groundwater surfaces, phosphorus removal can be compromised by the limited contact between effluent and underlying soil, and potentially by the flushing of phosphorous stored seasonally in soil during periods of infiltration.

Both water quality and habitat quality were issues for the designers of the first generation wetlands profiled here. Water quality concerns increasingly result in the use of numeric water quality standards in NPDES permits. The water quality data in Table 1 is available because numeric standards are used in these permits.

In Arcata, where both numeric standards and narrative beneficial use standards are used, an emphasis on the latter may have contributed to project success. Specification of beneficial use standards resulted in a design for the enhancement wetlands that provided for both treatment and habitat. The Arcata enhancement wetlands use a mix of open water and emergent vegetation that provides, in addition to treatment, waterfowl habitat (Weller, 1978). The Mt. View SD wetlands also support a mix of open water and emergent vegetation, the result of district efforts to create habitat while improving effluent quality.

The lack of a data set for Black Diamond comparable to the other treatment wetlands profiled here is unfortunate. Not only was Black Diamond the only natural treatment wetland (of the five profiled), it was also the only treatment wetland of the five that was established high in a watershed. Without a suitable data set, it is difficult to say whether "failure" at Black Diamond was due in part or entirely to the treatment facility, or in part or entirely to watershed location, or some other factor. Watershed location deserves consideration.

For any treatment facility, an upstream location may reveal problems more readily than a downstream, estuarine location. An upstream facility discharges to a freshwater environment with relatively sensitive receptors. For Black Diamond, a major feature of the downstream environment is Lake Sawyer. Coincidentally, Black Diamond and Lake Sawyer are located in King County, Washington, the location of pioneering studies on the effects of nutrients on lake productivity (Edmondson, 1991). A year-round audience of lake residents was available to observe and report perceived changes in lake conditions during operation of the Black Diamond facility. As a result, the Black Diamond system operated in a somewhat unique environment, a result of location within the watershed and watershed location.

A treatment wetland in the estuary encounters a different set of environmental conditions. The estuarine environment, with diurnal variations in water cover and salinity, is hostile to many aquatic species, and some sensitive species, such as salmonids, are not resident. Aquatic productivity may not be limited by phosphorus. Daily tidal action may remove evidence of poor performance. Commercial users in the estuary may be less sensitive to or more forgiving of environmental change than the upstream counterpart, the home owner. An estuarine location may be better for attracting species of observable wildlife, thereby increasing the opportunity for perceived improvements of beneficial uses. Perhaps not coincidentally, the Arcata and Martinez (Mt. View SD) treatment wetlands are located in estuarine environments.

Nonetheless, experiences in Arcata and Martinez, California suggest that treatment wetlands can be used to enhance regional habitat. Data from these two locations support pilot habitat assessment data collected at other treatment wetlands (McAllister, 1992; McAllister, 1993a; McAllister, 1993b). Treatment effluent has been used in one national wildlife refuge to restore wetland habitat functions (Hardy, 1989; McAllister, 1992) and has enhanced regional habitat at a number of other locations (US EPA, 1993).

In addition to replicating wetland habitat functions, treatment wetlands could replicate the nutrient processing function of historic wetlands and thereby contribute to overall watershed health, although research in this area is lacking. The downstream export of detritus from wetlands is an important wetland function; in estuaries, such detritus supports the juvenile salmonid food chain (Naiman and Sibert, 1979; Sibert, 1979; Healy, 1979). Upstream wetlands perform a similar processing function and provide refuge habitat for juvenile salmonids (Peterson and Reid, 1981).

Treatment wetlands could be used to replicate the functions and values of wetlands that have been "lost" to development in Puget Sound watersheds. The loss of these wetlands has been noted by state and federal resource agency staff working regionally and within specific watersheds (Puget Sound Water Quality Authority, 1986; Washington State Department of Ecology, 1993; US Army Corps of Engineers et al., 1993). Recently, Ecology has published new water reuse standards that may influence the manner in which treatment wetlands are developed in Washington State (Washington State Department of Ecology, 1997). Whether or not the habitat qualities of treatment wetlands developed elsewhere will be re-created here under new Ecology standards remains to be seen.

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Use of Salmonid Valuation in Resource Management: A Valuation Model for Use in Resource Protection and Enhancement Decisions

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Abstract

The public is constantly facing decisions on how to protect our natural resources, particularly fisheries resources, and how best to apply the limited resources available for these efforts. A generic valuation method for salmonid resources, presented in this pape, can be used to help make more informed resource management decisions in the Pacific Northwest. Recent studies on the value of commercial, recreationa,l and existence or non-use fishery values for salmon in the Pacific Northwest were reviewed. Using court-tested valuation methods, a range of values for several species of salmon was estimated and adjusted for inflation to current values. The salmonid valuation method was coupled with a fishery production, harvest, and escapement model using readily available statistics to estimate the value of salmonids for a particular run or project. The model was used to evaluate fishery enhancement projects to identify the most cost-efficient projects. It was also coupled with a basin-wide HSPF analysis of stormwater alternatives to estimate impacts to fishery valuation, allowing alternatives to be considered based on both the public and private cost development and the public cost to fishery resources. The method provides even small governments the ability to make more informed resource management decisions.

The Contribution of Reed-Canary Grass Dominated Low Gradient Streams to Juvenile Salmon Overwintering Habitat

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Muckleshoot Indian Tribe Fisheries Department

Abstract

This study assessed overwintering juvenile salmon use in reed canary grass-dominated low-gradient streams lacking the habitat features normally associated with salmon streams. Mill Creek in King County, Washington is a low-gradient tributary to the Green River. During the late summer, few juvenile salmonids use the low-gradient reaches due to elevated temperatures and low DO. During the late fall and early winter, juvenile salmon migrate from the Green River into Mill Creek to overwinter. Overwintering juvenile salmon use in Mill Creek was determined by electroshocking reaches of Mill Creek. Juvenile salmon sizes and densities were compared to those in streams of presumed higher value based on habitat measurements. The densities and sizes of overwintering juvenile coho in Mill Creek were comparable to, and at times exceeded, those found in streams rated as having superior habitat based upon standard methodologies. Given the right combination of factors, streams that appear to have poor salmonid habitat value, often provide a range of critical habitat functions for overwintering juvenile salmonids and contribute significantly to the available habitat. The removal of reed canary grass without consideration of its contribution to overwintering salmon may have adverse impacts upon pre-smolt production in a stream.

The Schel-chelb Estuary—A Successful Habitat Mitigation/Enhancement Partnership

Clay Patmont
Anchor Environmental, Inc.

Rick Singer
Environmental Affairs Office, Washington State Department of Transportation

Abstract

Constructed in 1997, the Schel-chelb Estuary is a new two-acre intertidal mudflat/saltmarsh located on Bainbridge Island. The project provides compensatory habitat mitigation for a related cleanup project, and other environmental objectives. The overall project represents a highly successful public-private partnership of more than 12 entities, all of whom benefited.

The Schel-chelb Estuary was initially conceived by USFWS and local sponsors as a habitat enhancement project, restoring a historic estuary on the site. Concurrently, WSDOT and other parties identified the Schel-chelb project as partial compensation for 0.9 acres of nearshore confined disposal facility (CDF) fill in nearby Eagle Harbor. Use of the CDF facilitated cost-effective sediment cleanup of the West Eagle Harbor Site, and also resolved a conflict between the need to expand the ferry maintenance facility and to maintain other community uses. Approval of the estuary as partial mitigation for the Eagle Harbor CDF fill site provided the necessary funding for project design and construction, which otherwise would not have been possible.

The combined Schel-chelb Estuary and Eagle Harbor cleanup projects increased the amount of high-quality aquatic habitat on Bainbridge Island, relative to existing conditions and other multi-project alternatives. The project may provide a good model for other public-private partnerships.

Coho Salmon Restoration in the Chimacum Watershed

Peter Bahls
Port Gamble S'Kllallam Tribe

Abstract

The objective of this 1996 study was to assess the potential for restoration of coho salmon (*Oncorhyncus kitsutch*) in a watershed dominated by agricultural land uses. Limitations on coho recovery were evaluated by comparing the existing conditions of the coho population and habitat to pre-European settlement conditions and identifying areas of habitat loss for each stage in the coho's freshwater life cycle. Existing conditions were assessed by field sampling of juvenile coho distribution and habitat parameters. Historical conditions were reconstructed based on oral histories, General Land Office surveys that were conducted between 1858–1874, and assorted maps, aerial photographs, and reports. We found that coho salmon habitat in the Chimacum watershed has decreased dramatically both in quantity and quality over the past 145 years. Removal of swamps, beaver ponds, and channel meanders by extensive ditching has eliminated over 90% of the historic summer and winter rearing habitat for juvenile coho in the watershed. Of this remaining fraction of habitat, most has been degraded by a combination of land-use impacts that have caused high temperatures, keyed to specific sites, include protecting existing refugia, correcting man-made fish passage barriers, and restoring rearing habitats and riparian zones. Several major restoration projects that have been completed based on the assessment are discussed.

The Salmon and Steelhead Habitat Inventory and Assessment Project: Stock Restoration from the Ground Up

Ted Labbe
Point No Point Treaty Council

Tom Ostrom
Pacific Watershed Institute

Abstract

The Salmon and Steelhead Habitat Inventory and Assessment Project (SSHIAP) goals are: to quantify current freshwater salmon habitat, to assess the effect of habitat degradation and loss on SASSI salmon stocks, and to develop stock- or watershed-based restoration projects. The project area includes all coastal and Puget Sound watersheds from the Canadian border south to the Chehalis River. An important product of SSHIAP will be a database linked to a geographic information system (GIS). This system delineates each stream network into 0.1–3.0-mile segments at the 1:24000 scale and contains information on fish distribution, migration barriers, channel modifications, and other habitat features. Preliminary analyses suggest that a broad-scale approach to quantifying human impacts on salmon habitat provides a necessary foundation for individual stock recovery and a framework for future research and restoration of salmon and steelhead in western Washington.

1A: The Watersheds Upstream

Questions & Answers

Q: Ted Labbe, is the progress of this project from north to south or some other organizational scheme?

Labbe: There are six biologists presently working on this project, and we each have our own region. We are each at various stages of completion with some of the basic building of the database, and I'd have to say, if you are interested in a particular area, finding out about whether it's been completed, I would have to refer you to that particular person. Generally we do work from north to south in each of our areas and from east to west. That's very general. We each have our own strategies.

Q: Is the web site up for the project?

Labbe: There is a web site up. It has yet to contain any data, access to any data. It's more for informational purposes for people about our web site. It's available through the Northwest Indian Fisheries commission web site, which, I believe, is www.mako.nwifc.org. You can search for the Northwest Indian Fisheries Commission and there will be a link to our project.

Q: Chris May, you were saying there was no threshold effect of impacts on water quality and hydrology as the impervious area even got up the 5 percent of the area. I wonder if you could comment on any responses from municipal planners when it comes to occupying land in drainage basins. They must get pretty depressed about this. Basically, what you're saying is that there is no level of development that they can argue does not have an impact on water quality.

May: To qualify that: there is no level of development at the current way we develop our watersheds. I alluded to the fact that I think one of the big answers to this problem may be to take a look at how we develop our watersheds, and incorporate some of the known common sense and otherwise new facts, if you will, to develop differently. And possibly, if that happens, maybe there is some threshold. I would just say that there is probably some panic about this.

Q: Is someone looking at possible ideas such as that we may have to stop development in certain sub basins to ensure the conservation of some of these habitats as we occupy the lowland?

May: In the late 1980's and early 1990's when some of these results were first being intimated, King County was in the process of developing zoning plans for the Bear Creek and Soos Creek basins, and one of the responses was, in fact, to down-zone certain areas that were judged to be of high habitat quality. It certainly didn't end development. But it substantially reduced the development expectations of a number of the property owners in that area.

Jacques White: I work for People for Puget Sound, and I am in a position to try to advocate to policy makers about particular decisions and moving in particular directions about restoring salmon and other resources in the Puget Sound basin. The talk that was given earlier today by Jeffrey Stern was very interesting because he had a cost-benefit analysis of protecting existing salmon resources depleted and otherwise. But when I hear talk about restoration, I feel like it's very difficult to make decisions on a cost-benefit basis. I haven't seen good analysis of doing a particular action in a particular type of area and, given the talk that was given by Dr. May earlier, it seems like there is very little reason to try to restore already degraded urban areas. So I was wondering, do any of the speakers know of a cost-benefit analysis for restoration as opposed to just protection actions.

A: Tim Beachy has done some work on restoration, I think it was in the Skagit, on restoration of agriculturally dominated watershed and the benefits of doing, let's say, side channel restoration vs. culvert replacement vs. riparian protection.

Comment: I'd like to suggest that cost-benefit isn't the only way to approach this. You probably realize that. Some more practical ways are just, for example, identifying funds of money that are there and how to increase them. Most counties, for example, have a conservation futures assessment on property right now that's not a significant assessment, but it does create a fair amount of money. I know the city of Tacoma raises about $400 dollars a year in its conservation assessment, which is about a quarter of what's raised in Pierce County. Maybe a starting point is to say, well, what if we multiplied that by four—what would that effect be? And just start thinking in absolute terms rather than cost-benefit.

Comment: I should mention that Jeff Stern wasn't able to stay because he is at the county council right now arguing for improved drainage standards on new development to protect fish habitat.

Q: Should buffers be increased from standard forest practice requirements if the land is to be converted to urban uses.

A: Yes. I think the buffer issue has to be revisited a bit. I don't think we know what is an adequate riparian buffer for an urban area. Just to define buffers for "urban" areas is kind of simplifying it because I think it would depend on your land use within that area. Most buffers standards now are based on either agricultural or forest practices, and we need to look at specifically what we need to do with those buffers in conjunction with stormwater best management practices and the whole suite of other watershed methods to prevent degradation or rehabilitate a stream. Currently we map out our buffers and developers are typically pretty good about keeping to those buffers. But after the development becomes a neighborhood, there's no delineation there. There's no active education given to the homeowners. And typically we find that encroachment from homeowners is fairly prevalent. Buffers that start as 100 feet can go down to almost nothing in five years. To some extent it's like comparing apples and oranges: forest practices and urbanization. Because a clear cut grows back eventually, or it's planted. Northgate Mall does not grow back. And there are always people in urban areas, working, doing things in the buffer area. In contrast, that's not true in most forest areas. I mean, they come in and then they're out. It's a totally different issue, and I think to base one on the other is to ignore a problem.

PUGET SOUND RESEARCH '98

SESSION 1B

NUTRIENT ISSUES IN PUGET SOUND—BUDD INLET

Session Chair:

Curtis C. Ebbesmeyer

Evans-Hamilton, Inc.

Net Water Movement in Budd Inlet: Measurements and Conceptual Model

Curtis C. Ebbesmeyer and Carol A. Coomes
Evans-Hamilton, Inc.

Venkat S. Kolluru and John Eric Edinger
J.E. Edinger Associates, Inc.

Introduction

Previous oceanographic studies of Budd Inlet assumed a two-layered flow pattern typical of estuaries, i.e., the upper water layer flowing out of the inlet above a deeper, inflowing stratum (URS Corporation, 1986). We examined this assumption during a year-long field program to assess the effects of permitting additional effluent into the inlet from the Lacey-Olympia-Tumwater-Thurston County (LOTT) wastewater treatment plant. The field measurements and a three-dimensional (3-D) hydrodynamical model led to a new dynamical framework for the inlet's flow.

Budd Inlet's circulation was monitored along a number of east-west oriented transects (Figure 1). South of the BA transect, the inner inlet's northern boundary, the flow is largely controlled by gated discharges from Capitol Lake and large tidal ranges that daily expose extensive tide flats. North of the BA transect, the estuarine flows are primarily separated laterally rather than vertically, as shown later in this paper.

Physical Setting

Budd Inlet, Puget Sound's southernmost marine water body, composes 0.15% of the Sound's total volume at mean high water (MHW) (McLellan, 1954). Because the tide range generally increases with distance inland, the inlet's range is penultimate in Puget Sound (14.4 feet; 4.4 m). Table 1 lists selected physical characteristics of the inlet.

Table 1. Budd Inlet: selected physical characteristics.

	Non-Metric Units	Metric Units
Inlet length from mouth to head[1]	6.8 statute miles	10.9 km
Width at mouth[3]	0.99 statute miles	1,600 m
Fresh water input during November 1996 from:		
LOTT sewage treatment plant	11 mgd[2]	0.48 m^3/sec
Direct rainfall on inlet[4]	34 mgd	1.5 m^3/sec
Inlet net inflow along western shore[5]	6,875 mgd	300 m^3/sec
Capitol Lake (average)	350 mgd	15 m^3/sec
Capitol Lake (gates closed ~ 48% of time)	0	0
Capitol Lake (gates open ~ 52% of time)	672 mgd	30 m^3/sec
Tide range (diurnal[6])	14.4 feet	4.39 m
Inlet volume below mean higher high water (MHHW)	301,000,000 yd^3	230,000,000 m^3
Inlet water surface area at:		
mean high water (MHW)	8.8 square miles	22,680,000 m^2
mean lower low water (MLLW)	7.2 square miles	18,560,000 m^2
Mean inlet depth (volume/surface area)	30 feet	10 m
Flushing time (Inlet volume @ MHHW/inflow net transport)	7–11 days	600,000–950,000 sec

[1] From the Capitol Lake gates to the inlet Mouth (center of the line connecting Dofflemeyer and Cooper points);
[2] million gallons/day
[3] Line connecting Dofflemeyer and Cooper points;
[4] Rain falling on the inlet's surface area at MHW;
[5] Through the cross section near inlet mouth;
[6] Diurnal tidal range equals MHHW minus MLLW.

The Deschutes River empties into Capitol Lake which in turn discharges to the southern terminus of the inner inlet via control gates so as to maintain a nearly constant lake level (Davis et al., 1998). The long-term monthly average Deschutes discharge varies from a maximum during January of approximately 600 cfs (17.0 m^3/sec), to a minimum during August of 50 cfs (1.4 m^3/sec). Superposed on the seasonal swing are discharge pulses caused by periodically opening the gates. For several hours a day, the lake discharges as if it were a substantial river; for most of the day, however, it discharges no fresh water. During the extremely wet winter of 1996–1997, for example, discharge during gate openings often exceeded 100 m3/sec and reached 300 m^3/sec.

Methods

The inlet's flow was ascertained from field observations (water properties, currents) and a hydrodynamical model.

Water Properties

Temperature, salinity, density, and dissolved oxygen were measured versus depth using Seabird conductivity-temperature-pressure (depth) CTDs lowered from two vessels (models SBE 19 and 25 equipped with AFM modules and rosette water bottles). From September 1996 through September 1997 during 23 cruises each lasting a day, 27 locations along and across the inlet were sampled.

Current Meter Observations

Water flow was monitored with current meters moored for a year at three sites (Figure 1): sites 1 and 2, on the west and east sides of the BE transect, respectively, were taken as representative of the inlet's mouth; and site 3, on the west side of the BC transect in the central inlet. Currents also were measured for a month at several other sites (see Figure 1).

Two types of current meters were deployed: 1) Acoustic Doppler Profilers (ADPs; RDI broadband 300 kHz and Sontek 1500 kHz) placed on the bottom measured currents between a few meters of the sea surface and sea floor. Current speed and direction were averaged for two minutes every 15 minutes in 0.5 and 1 m depth intervals (bins) at sites 1–4. To filter out tidal variability, the observations within each depth bin were vector-averaged over one tidal day (24.84 hours) and 28 calendar days. 2) Aanderaa current meters were moored at fixed depths. Current speed was averaged during 15-minute intervals, at the end of which current direction was recorded.

Additional, more detailed, current measurements were made to examine the velocity structure across the inlet's mouth: 1) during 14–15 March 1997, an ADP was mounted over-the-side while the vessel (*R/V Reflux*) made 24 crossings of the BE transect; 2) during September 1997, two ADPs were deployed at sites 1 and 2 toward the west and east sides of the inlet, respectively, while three Aanderaas were moored at mid-channel.

Hydrodynamic Model

For comparison with the current measurements and water properties, the 3-D hydrodynamic and transport model known as GLLVHT (Edinger and Buchak, 1995) was programmed to compute water transport west and east of a north-south line approximately dividing the inlet in half (see Figure 1). Calculated water transport was averaged during 28-day intervals; these were then averaged during November 1996–January 1997.

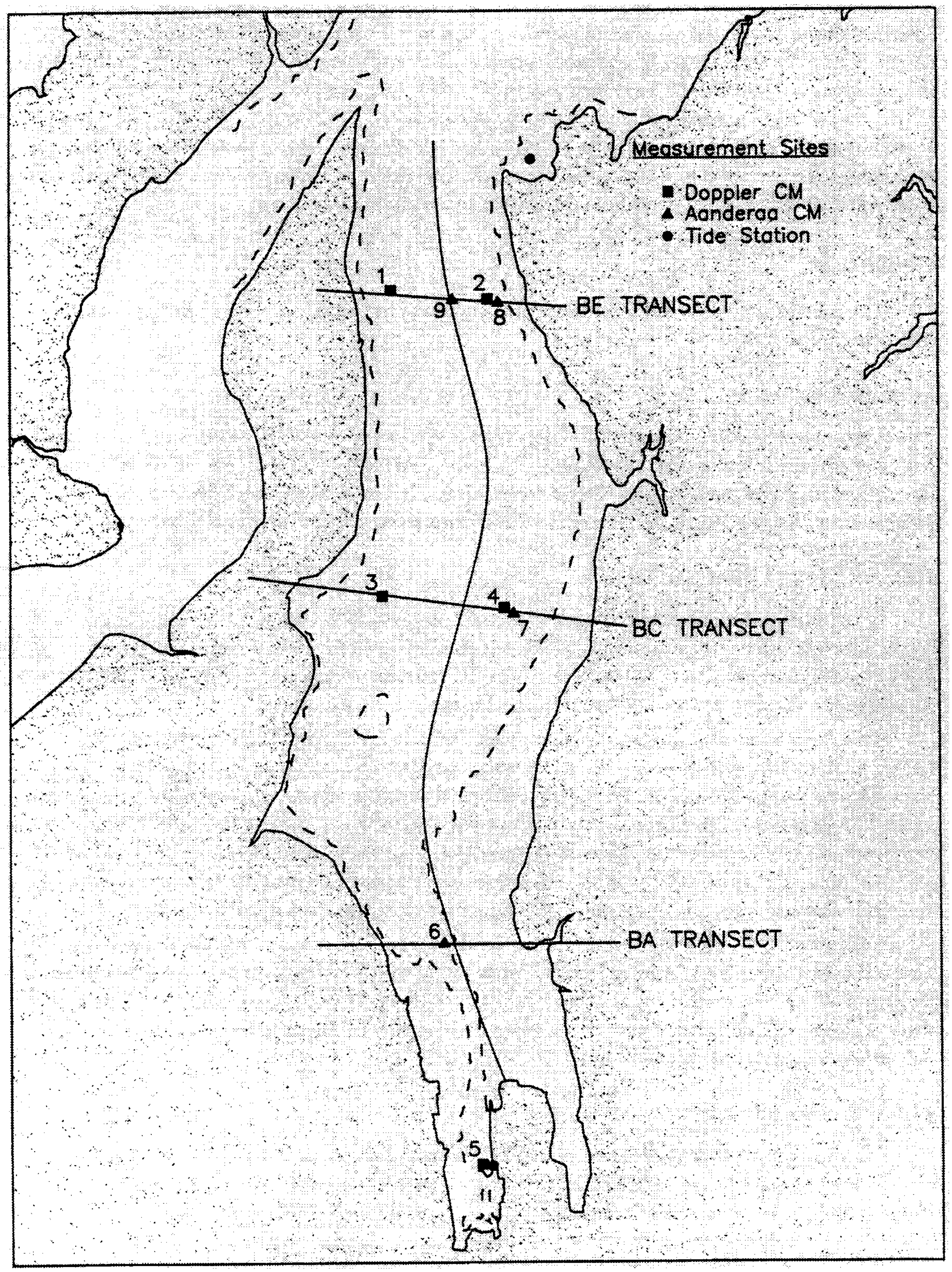

Figure 1. Locations of current meters and transects in Budd Inlet. Squares denote ADP current meters on the sea floor; triangles, Aanderaa current meter moorings; circles, water level recorders; transect lines, outer (BE), central (BC), inner (BA); dashed line, the 18-foot depth contour from bathymetric surveys. Net transports were computed west and east of the line down the center of the inlet.

Results: Water Properties

Water properties were contoured throughout the inlet in horizontal planes at constant depths, and across the inlet in vertical planes along the transects. The thousands of planes contoured showed similar water mass patterns throughout the year. For illustrative purposes, the depth plane nearest the sea surface (0.5 m) was chosen to trace the plume of fresh water from Capitol Lake (Figure 2). The BC transect was chosen to illustrate the cross-inlet structure, because four as opposed to three or fewer stations on the other transects were sampled along it (Figures 3 and 4).

In each season at 0.5-m depth, the contours of temperature, salinity, density, and oxygen were generally oriented north-south, indicating that Capitol Lake effluent traveled northward as a plume along the inlet's eastern shore. More saline Puget Sound water flowed southward along the western shore. Illustrative contours for spring (16 April 1997), show the freshwater plume as approximately 0.6 _C warmer, 2 ppt less saline, 1 sigma-t units less dense, and 1–2 mg/L more oxygenated than the water flowing southward along the western shore.

The separation line between the inflowing and outflowing currents was observed during July 1997, when operators drained Capitol Lake to perform annual maintenance (removal of undesirable plants). A few days afterward a rip line containing large amounts of plant material floating on the water surface was photographed. The line extended seven miles from Capitol Lake northward through the outer inlet. Comparison with the water property contours indicated that the plant debris traced the separation between the inflowing and outflowing currents.

Taken together, the 23 cruises spread over a year showed plumes of relatively low salinity water along the eastern shoreline in 70% of the density and 83% of the salinity contours in the 0.5-m depth plane. Furthermore, closed temperature and oxygen contours at 0.5 m revealed elevated levels in the central inlet indicative of a gyre. Closed contours were found in 22% of the temperature and 57% of the oxygen contours.

Contours across each transect almost always showed the plume as a lens along the eastern shore (Figures 3, 4). The salinity difference between the lowest values in the plume and the highest values in the Puget Sound water along the western shore is a fundamental estuarine parameter. Along the BC transect the difference varies from 6 ppt during fall and winter to 2–3 ppt during spring and summer. As the plume is both warmer and less saline than the source waters feeding the inlet, and since both temperature and salinity act to decrease density within the plume, the density contours mimic those of temperature and salinity.

In the cross-sectional contours, the oxygen concentrations are higher than in the source waters by 1– 2 mg/L during fall and winter, a difference increasing to 3–6 mg/L during spring and summer. Note that the minimum oxygen concentrations occur approximately beneath the surface plume flowing northward along the eastern shore (Figure 4).

Regardless of water property, the inlet's water mass was separated laterally across the inlet, a structure reflected by the current measurements.

SPRING

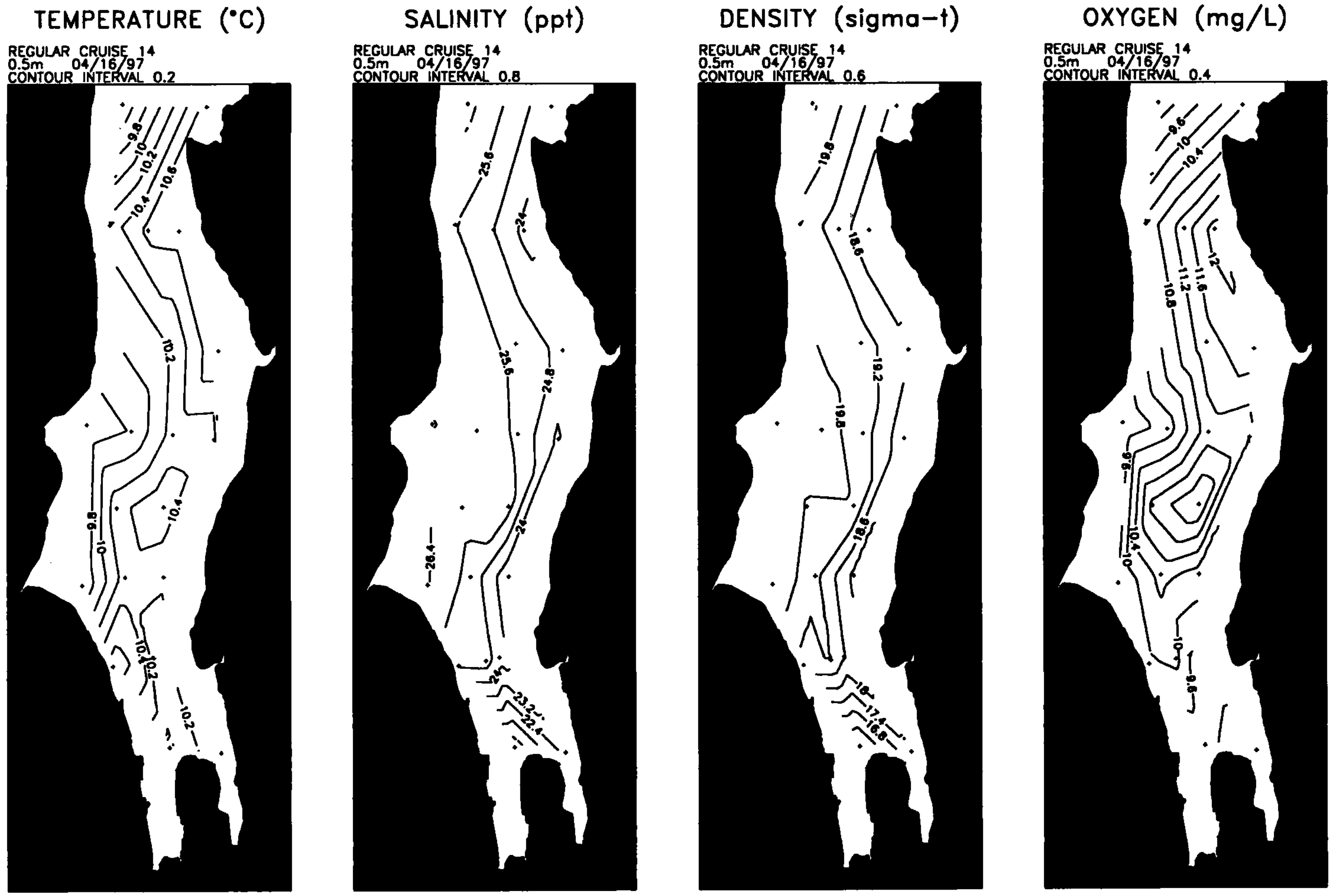

Figure 2. Spring (16 April 1997) near-surface (0.5 m) contours (from left to right): temperature, salinity, density, and dissolved oxygen. Dots indicate locations of CTD profiles. Note that the contour interval changes with season.

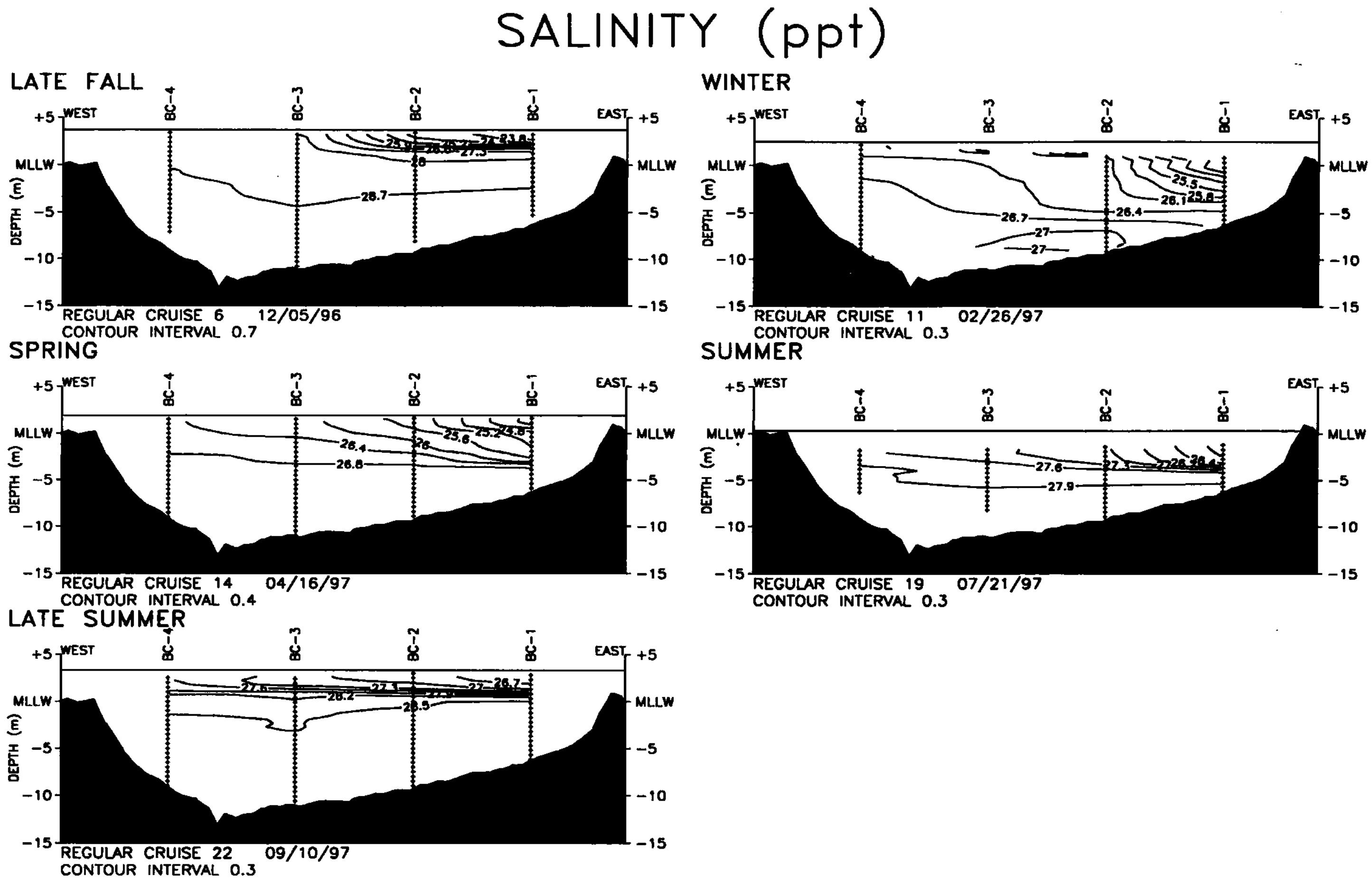

Figure 3. Seasonal salinity contours along the BC transect (left to right, top to bottom): Late Fall, 5 December 1996; Winter, 26 February 1997; Spring, 16 April 1997; Summer, 21 July 1997; Late Summer, 10 September 1997. Dots indicate CTD data. Note that the contour interval changes with season.

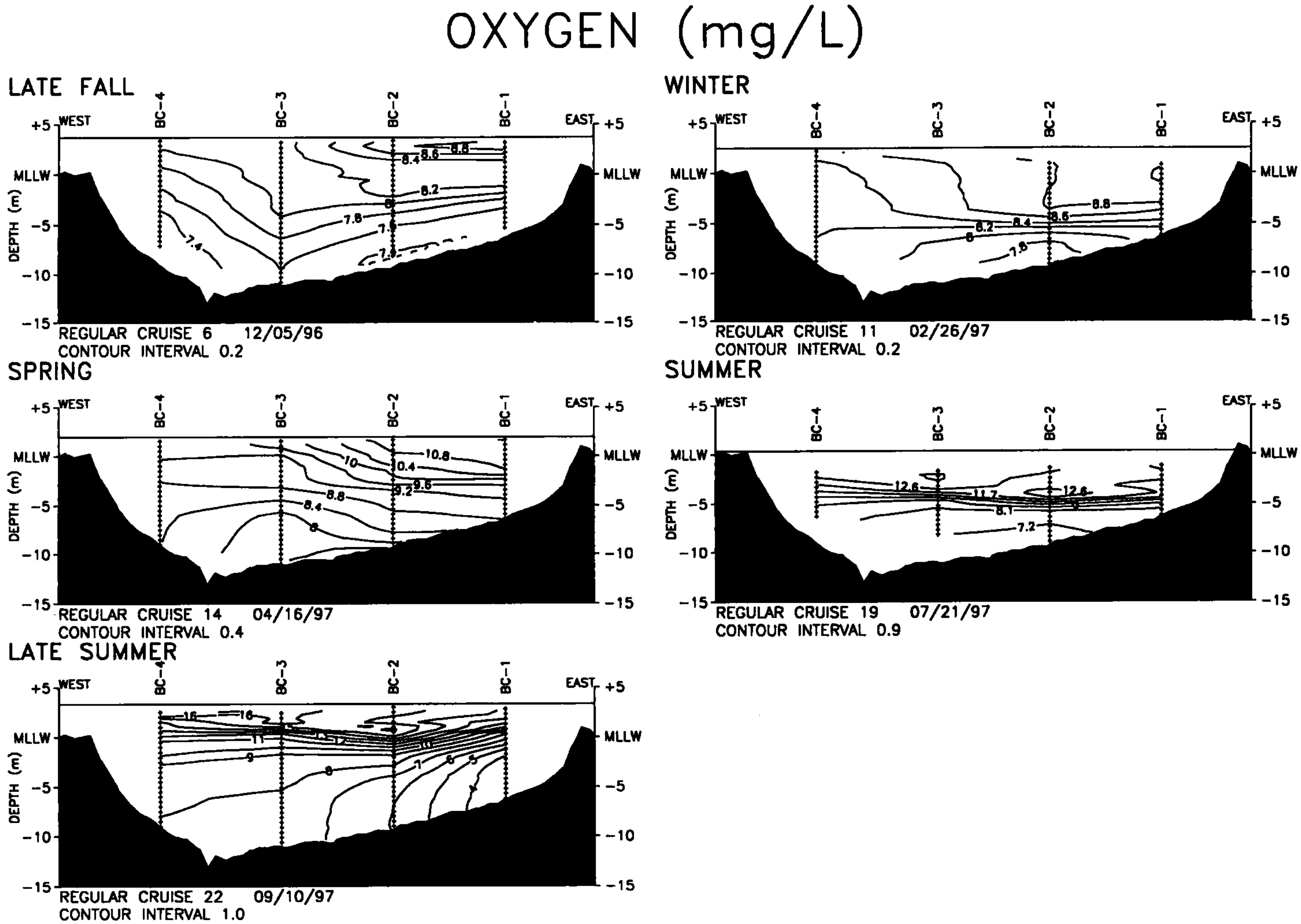

Figure 4. Seasonal dissolved oxygen contours along the BC transect (left to right, top to bottom): Late Fall, 5 December 1996; Winter, 26 February 1997; Spring, 16 April 1997; Summer, 21 July 1997; Late Summer, 10 September 1997. Dots indicate data. Note that the contour interval changes with season.

Results: Velocity Structure

To examine the current structure across the inlet's mouth, north-south current speed (V), as averaged for a tidal day and 28 calendar days, was contoured along the BE transect (Figure 5). Both sets of more detailed cross-inlet velocity measurements showed that the mean inflow and outflow are separated laterally by a line of no-net-motion (zero-speed contour) centered over the hump between the flood (west) and the ebb (east) tidal channels.

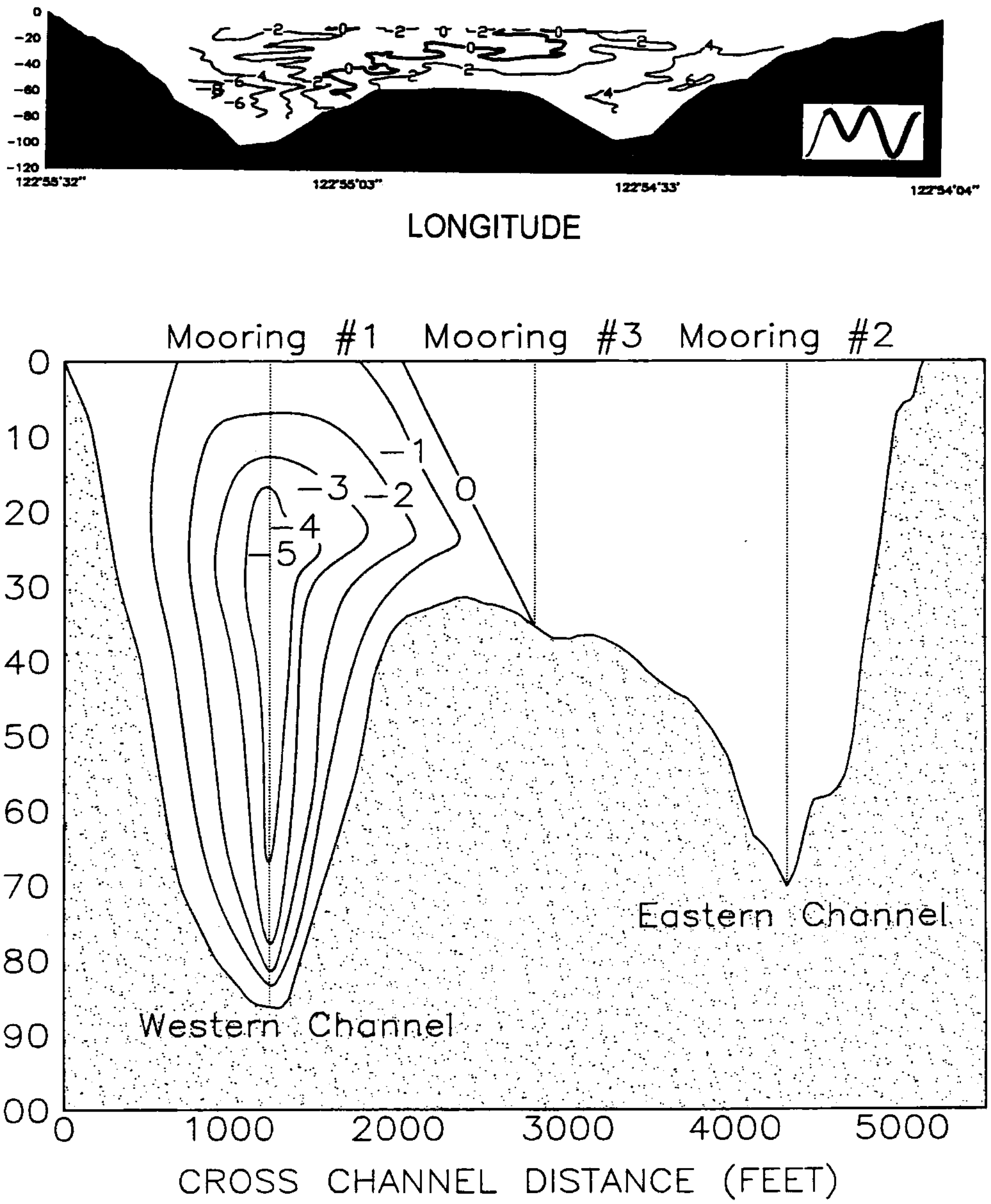

Figure 5. Current speed across Budd Inlet: detailed examination. The cross-channel structure of the average north-south currents was contoured with two kinds of averages (see Figure 1 for transect locations). Upper panel: 24 crossings of the BE transect with an ADP mounted over the side during a 25-hour survey during 14–15 March 1997, where the contour interval equals 2 cm/sec. Inset at lower right shows the tide over which the transects were averaged. Lowerpanel: 28-day averages based on Aanderaa current meters moored over the mid-channel hump (Mooring 3) and ADP observations in the flood (western) channel, where the contour interval equals 1 cm/sec. Note that in each panel, the zero-speed contour or line

of no-net-motion lies over the mid-channel hump.

For comparison with the hydrodynamical model, water flow into the inlet was expressed in discharge units known as volume transport. Net north-south current speeds derived ADP profiles were averaged for integer numbers of 28 days within a five-month period and contoured along transects across the outer and central inlets (Figure 6). Net volume transports of the inflows and outflows were then estimated from the contours (Table 2). Volume transports computed from the measurements and hydrodynamic model differed to a small degree (3–12%).

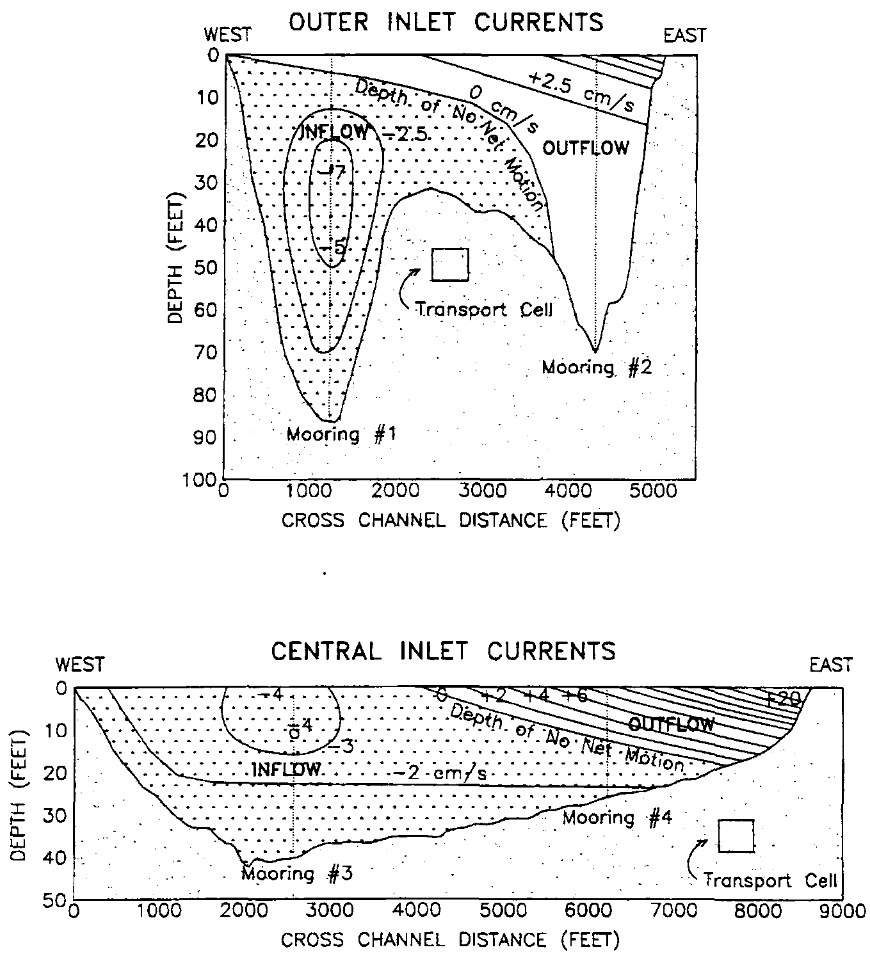

Figure 6. Current speed across Budd Inlet: currents during the hydrodynamical model runs. Top panel: outer inlet contours are based ADP observations at sites (Moorings) 1 and 2 on the west and east tidal channels, respectively. Bottom panel: Central inlet contours are based on sites 3 and 4 on the west and east sides of the channel, respectively. Northward transport was computed for the region of the cross section having positive speeds, and southward transport for the area of negative speeds (stippled). No net north-south motion occurs along the zero-speed contours. Transport cells represent the cross sectional unit areas in which transport was computed; these were summed to obtain the overall transport.

The north-south speed contours show the major features of the tidally averaged flow (Figures 5, 6). In the outer inlet a submerged core of higher velocity heads southward along the western shore, and a shallow plume of higher velocity moves northward along the eastern shore (Figure 6, upper panel). A similar pattern occurs in the central inlet, except that the western core of high velocity may extend to the sea surface, and the high-velocity outflowing layer is deeper and wider along the eastern shore (Figure 6, lower panel).

Table 2. Transports in Budd Inlet's inflowing and outflowing layers computed from current measurements and the hydrodynamic model. The current measurements were averaged during November 1996 through April 1997; hydrodynamic model results apply to 6 November 1996 through 31 January 1997. ***, the outflowing layer was too shallow to be sampled by the ADP at site 2 (see Figure 1 for locations).

Transect	**Water Transport (m^3/sec)**					
	South flow/ west shore			**North flow/ east shore**		
	Model	Meas.	% Difference	Model	Meas.	% Difference
Outer	-274	-281	3%	+315	***	
Central	-336	-352	5%	+374	+333	12%
Inner	-163	no data	---	+199	no data	---

Based on transports computed from the field data and the hydrodynamic model, schematic circulatory diagrams were constructed (Figures 7 and 8). For the volume transports associated with 16 or so elements of the flow patterns, see the captions in Figures 7 and 8. In general, approximately half of the outer inlet inflow reverses direction in the central inlet and exits via the outer inlet. Coriolis acceleration drives the inflows and outflows to the west and east sides of the inlet, respectively, augmenting the lateral flow separation. A secondary fraction recirculates in a gyre around the central inlet.

The forces driving the circulation were confirmed by the GLLVHT hydrodynamic and transport model. Figure 9 shows the model-computed circulation and surface salinities through a tidal cycle in the summer months. It shows on falling tide that there is still some inflow along the western side at the outer boundary and a gyre in the center of the inlet. As the tide falls, the currents become intensified along the eastern shore of the inlet. On a rising tide, the inflowing current is intensified along the western shore of the inlet

The modeled surface salinities in Figure 9 show that the low-salinity lens extending outward along the eastern shore on a falling tide produces a lateral distribution of salinity similar to that found from the data as shown in Figure 2 and Figure 3. The lateral distribution of salinity persists throughout the tidal cycle.

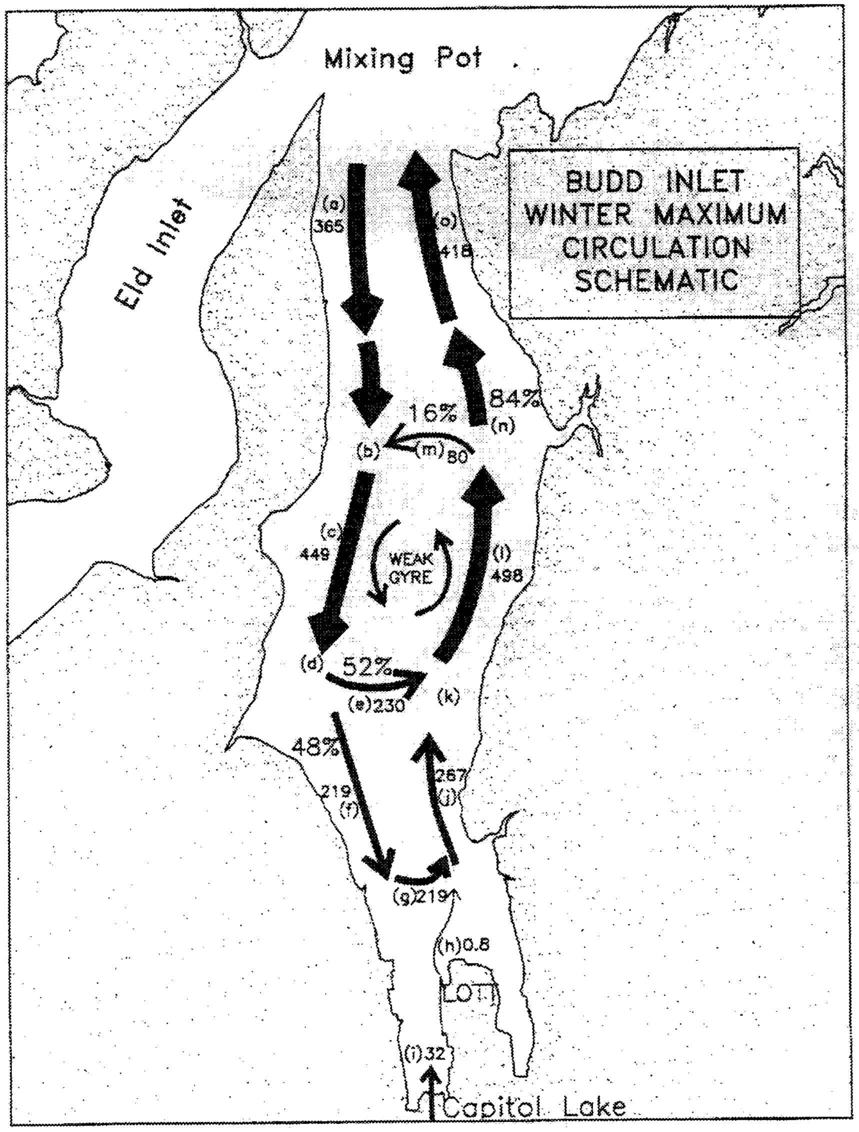

Figure 7. Plan view of Budd Inlet circulation during January 1997. The arrows indicate water flow scaled in thickness approximately proportionate with net volume transport (m^3/sec). Refluxing is shown by the percentages of the main flows diverted east and west across the inlet forming the weak gyre in the central inlet. Letter codes (a – o) following the water flow clockwise around the inlet denote the following: a) from the mixing pot the outer inlet main inflow transports southward 365 m^3/sec as a submerged jet-like current hugging the western shore of the outer inlet; (b) outer inlet main inflow merges with water refluxed from the outflow in the Central inlet; c) main inflow in the Central inlet equals 449 m^3/sec comprised of 82% water from the outer inlet (365 m^3/sec) and 18% water refluxed from the central inlet main outflow (80 m^3/sec); d, e) Central inlet main inflow diverges with approximately half (48%; 219 m^3/s) flowing into the inner inlet, and half refluxing (e; 52%; 230 m^3/sec) around the weak central inlet gyre; f) inner inlet main inflow (219 m^3/sec) moves southward to the vicinity of the LOTT outfall; g, h, i) inner inlet main inflow merges with discharges from LOTT (h) and Capitol Lake (i); j) inner inlet main outflow (267 m^3/sec) exits primarily as a thin (order of few meters thick) layer; k) inner inlet main outflow merges with water refluxed from the Central inlet main flow; l) Central inlet main outflow in a thin layer a few meters thick (498 m^3/sec) flows around the east side of the weak gyre; m, n) Central inlet main outflow diverges (n) with a secondary fraction (m; 16%; 80 m^3/sec) refluxing westward into the Central inlet main inflow (b, c); and (o) outer inlet main outflow (418 m^3/sec) exits northward to the mixing pot.

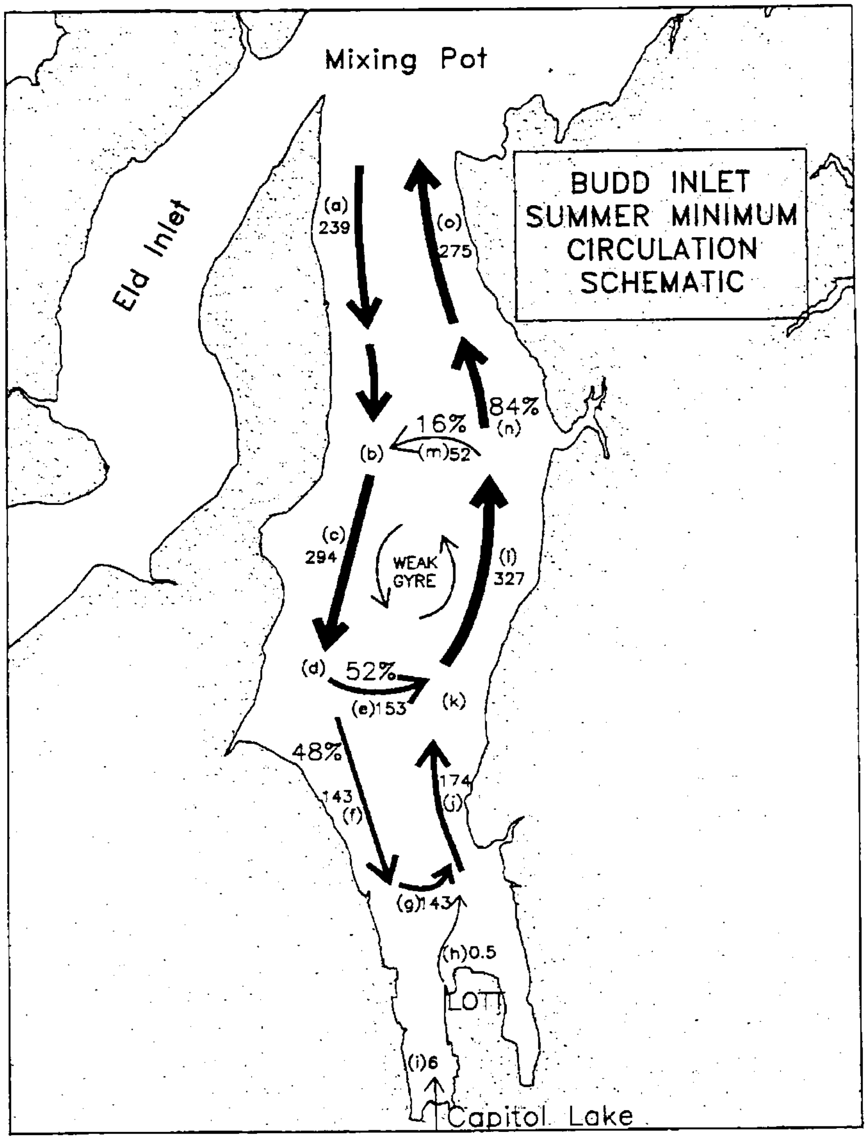

Figure 8. Plan view of Budd Inlet circulation during August 1997. The arrows indicate water flow scaled in thickness approximately proportionate with net volume transport (m^3/sec). Refluxing is shown by the percentages of the main flows diverted east and west across the inlet forming the weak gyre in the Central inlet. Letter codes (a – o) following the water flow clockwise around the inlet denote the following: a) from the mixing pot the outer inlet main inflow transports southward 239 m^3/sec as a submerged jet-like current hugging the western shore of the outer inlet; b) outer inlet main inflow merges with water refluxed from the outflow in the Central inlet; (c) main inflow in the central inlet equals 294 m^3/sec comprised of 82% water from the outer inlet (239 m^3/sec) and 18% water refluxed from the central inlet main outflow (52 m^3/sec); d, e) Central inlet main inflow diverges with approximately half (48%; 143 m^3/sec) flowing into the inner inlet, and half refluxing (e; 52%; 153 m^3/sec) around the weak central inlet gyre; f) inner inlet main inflow (143 m^3/sec) moves southward to the vicinity of the LOTT outfall; g, h, i) inner inlet main inflow merges with discharges from LOTT (h) and Capitol Lake (i); j) inner inlet main outflow (174 m^3/sec) exits primarily as a thin (order of few meters thick) layer; k) inner inlet main outflow merges with water refluxed from the Central inlet main flow; l) Central inlet main outflow in a thin layer a few meters thick (327 m^3/sec) flows around the east side of the weak gyre; (m, n) Central inlet main outflow diverges (n) with a secondary fraction (m; 16%; 52 m^3/sec) refluxing westward into the central inlet main inflow (b, c); and o) outer inlet main outflow (275 m^3/sec) exits northward to the mixing pot.

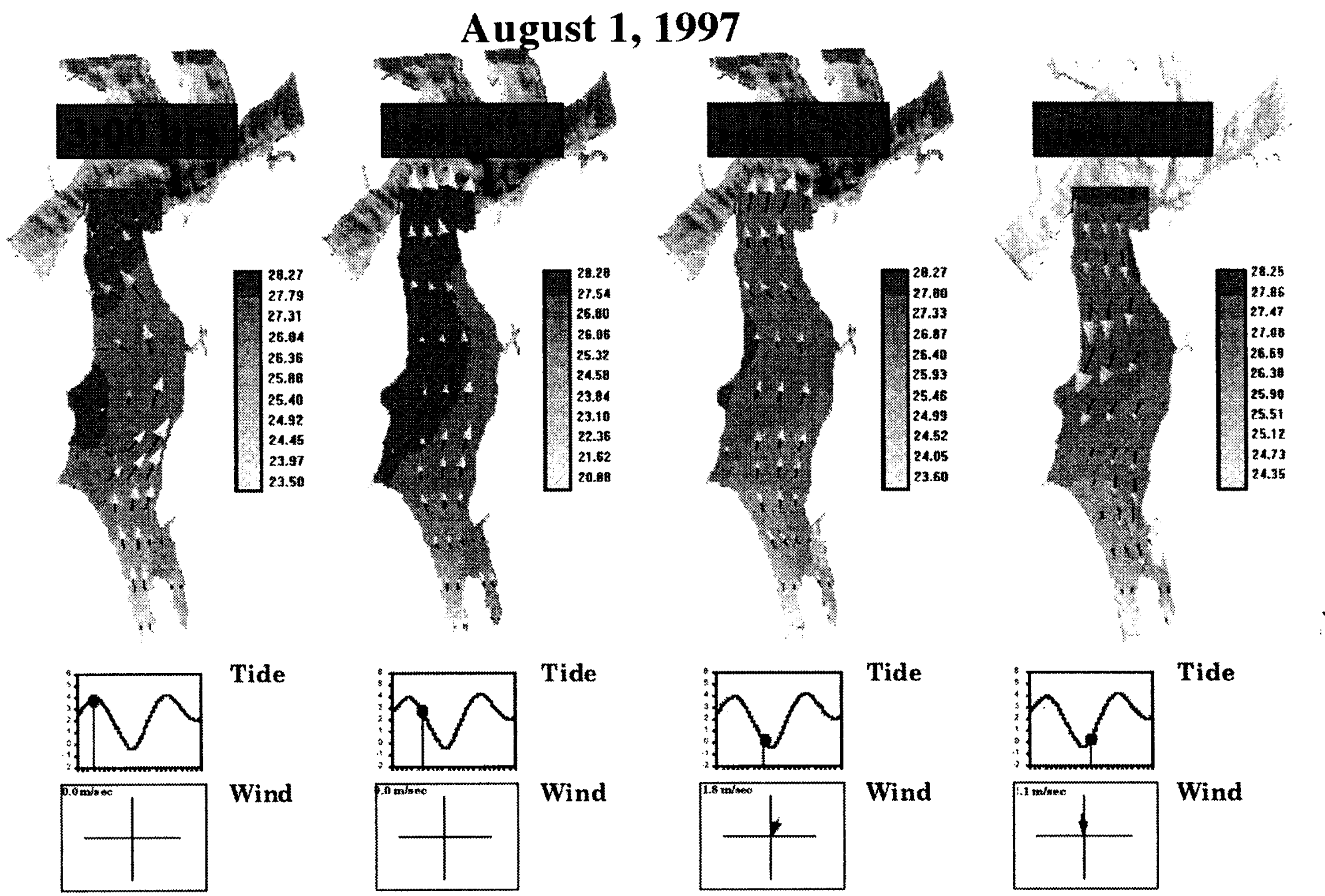

Figure 9. Surface velocities and salinity through a tidal cycle from the GLLVHT model. Time and tide proceed left to right as shown at top and bottom, respectively.

Results: Transport and Flushing

To evaluate how fast Puget Sound water enters the inlet, southward transport was computed from north-south speed contoured across flood tidal channel in the BE transect (e.g., Figure 5, lower panel). Eleven 28-day average ADP profiles were contoured assuming zero no-net-current at mid-channel (above the outer inlet mid-channel hump).

A regression fit to the 11 estimates of the estuarine volume transport (T) and Capitol Lake discharge (Q) data averaged for 28 days, yielded the following equation (Figure 10):

T	**=**	**222**	**+**	**3.61Q,**	**(1)**
Volume transport		**Tidal pumping**		**River effect**	

where: T= southward transport through the BE transect (m^3/sec); Q=Capitol Lake discharge (m^3/sec); r=correlation coefficient (0.861; and n=sample size (11).

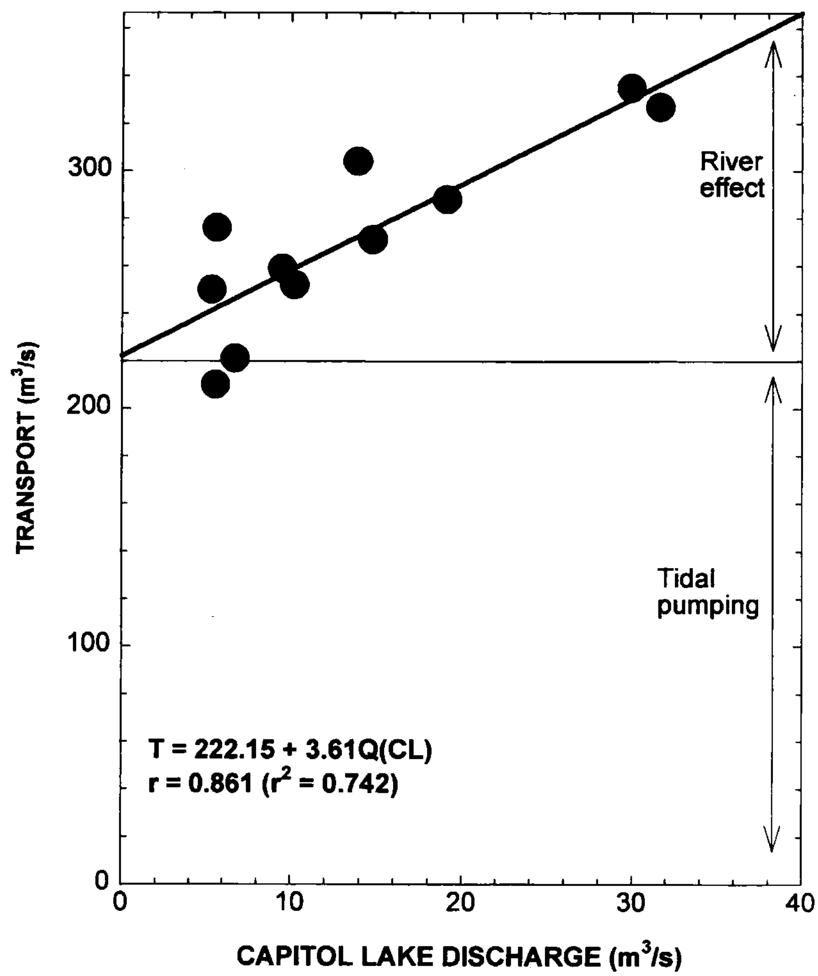

Figure 10. Estuarine transport versus Capitol Lake discharge. Dots represent 28-day average transports southward across the BE transect (see Figure 1 for location) and corresponding discharge from the Deschutes River via Capitol Lake. Equation and regression coefficient (r) represent the linear regression fit (see equation 1).

To evaluate whether the transports adequately represented a seasonal cycle, the inflowing currents measured at site 1 were further examined. First, 28-day average north-south speeds were displayed versus depth for the entire field year (Figure 11). Each profile showed southward flow from near the sea surface to the sea floor with maximum southward speed near a normalized depth of 0.6 m. Second, the north-south currents at the maximum inflow depth (~8m) depth were filtered with running tidal day and 28-day filters (Figure 12, upper panel). It can be seen that the daily values vary through a well-behaved seasonal cycle and the 11 transport estimates capture the extremes of this cycle.

Flushing (F) was estimated as the time for the net inflowing transport to replace the inlet's volume at MHHW, or F = [230,000,000/(222 + 3.61 Q)]/86,400 days, F = 2,662/(222 + 3.61Q) days. Values of F for the field year fluctuated from about 7 days in winter to 11 days in summer.

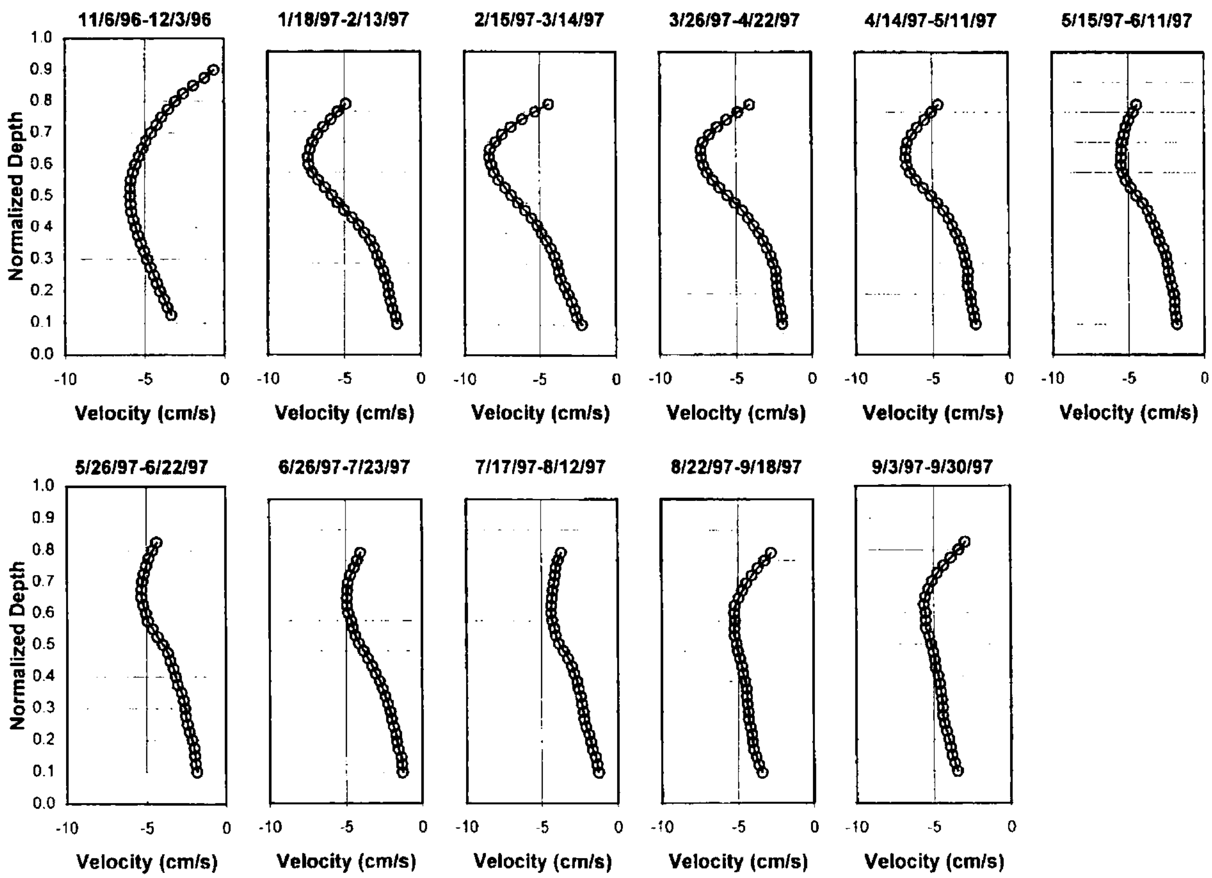

Figure 11. Vertical profiles of 28-day average north-south current speed at site 1. These 11 profiles were used to compute the volume transports (11 panels, left to right, top to bottom; see Figure 1 for mooring location). The 28-day average profiles begin in November 1996 and continue through September 1997.

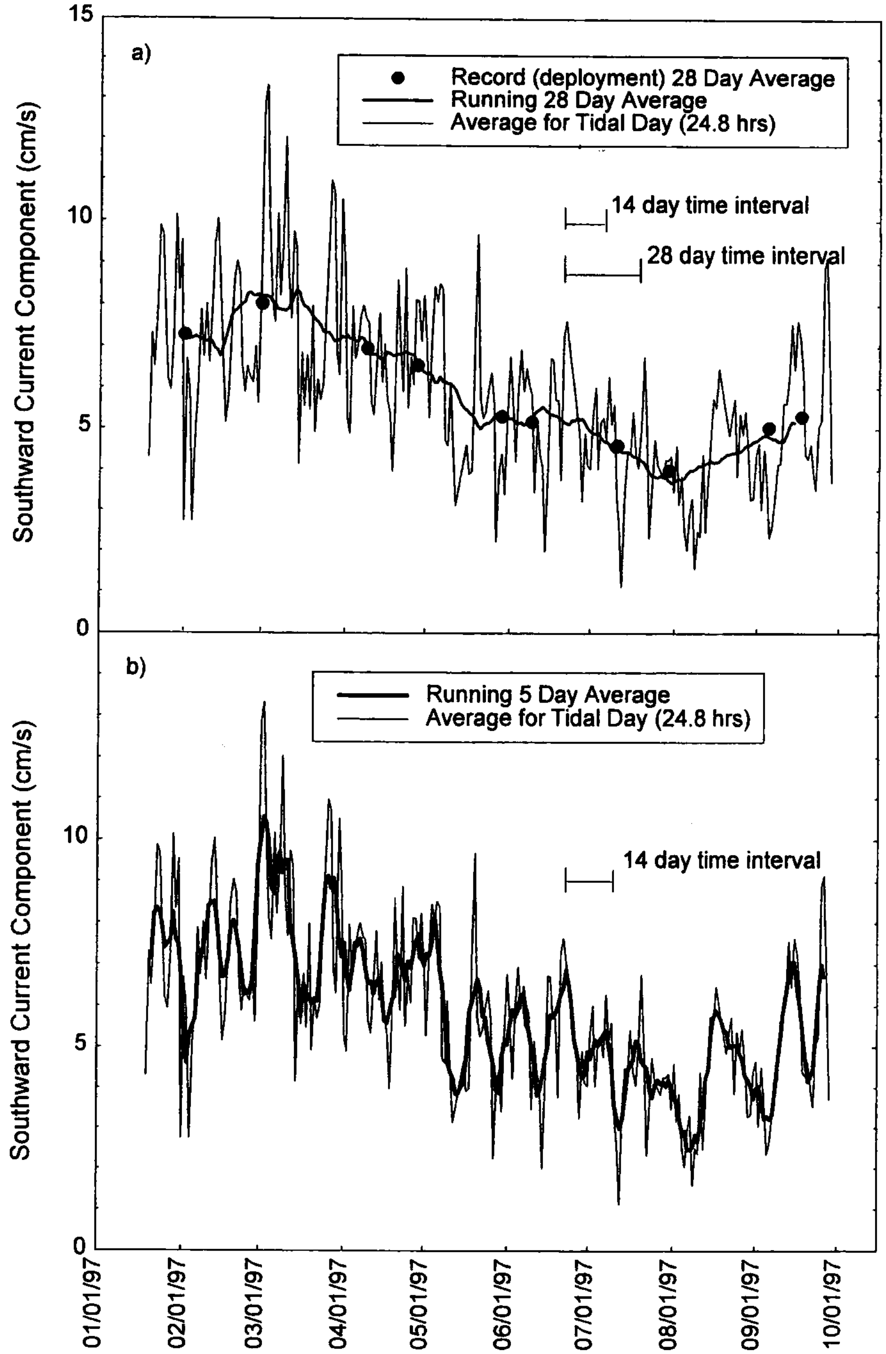

Figure 12. Seasonal cycle of maximum inflowing currents at site 1. In both panels the lighter solid line was obtained by averaging the ADP data at 8-m depth over 24.84-hour intervals. Top panel: heavier solid line, 28-day running average of the daily values; heavy dots, the mid-points of the 28-day intervals during which volume transports were calculated along the BE transect (see Figure 1). Bottom panel: heavier solid, 5-day boxcar running average of the daily values.

Tidal Pumping

The regression coefficient for equation (1) indicates that Capitol Lake discharge explains 74 percent of the outer inlet transport variance. Since Capitol Lake discharge during the field year fluctuated by approximately 35 m^3/sec, the addition of fresh water to the inlet explains approximately 126 m^3/sec of the outer inlet's transport compared with the much larger constant transport of 222 m^3/sec in equation (1). Furthermore, to preserve continuity within the inlet, a physical mechanism must lift the inlet's thick, deep inflow into its shallow outflowing layer. Therefore, we searched for a physical mechanism that upwelled water at the inlet's head at a rate equal to the constant in equation (1).

Several factors suggested tidal dynamics as the upwelling mechanism:

1. Tidal dynamics within Puget Sound are well known to undergo pronounced variations at two-week intervals. Power spectra of the daily net north-south speeds at site 1 showed a significant peak at a period of two-weeks (Dr. Robert J. Stewart, personal communication). In the time-series of daily net speeds smoothed with a five-day running average, the speed maxima are separated by an average of two weeks (Figure 12, lower panel).
2. The shape of the sea floor and the intertidal volumes suggested a tidal mechanism. On the western side of the inlet, the 18-foot depth contour intrudes southward forming an upwelling channel for the flooding currents. On the eastern side, the outflowing layer is underlain by shallower depths deposited from Capitol Lake discharges that rain sedimentary materials downward from the outflowing layer.
3. The volume of water between high and low tides increases markedly toward the head of the inlet (Table 3). For the entire inlet the volume between Mean-Higher-High Water (MHHW) and Mean-Lower-Low Water (MLLW), taken as the tidal prism, approximately equals the volume below MLLW (ratio in Table 3). Southward, the ratio increases dramatically, reaching 2.72 in the inner inlet. On the average each day, the tide drains approximately 73% of the inner inlet's volume at the tide's highest stand.

Table 3. Water volumes within Budd Inlet segments below high and low tides. Notation: MLLW, mean lower low water; MHHW, mean higher high water.

	Volume (10^6 m^3)			
Inlet Segment	MHHW (1)	MLLW (2)	MHHW-MLLW (3)	RATIO (3)/(2)
Entire inlet	230.1	119.0	111.1	0.93
Central + Inner	131.1	60.0	71.1	1.19
Inner	35.4	9.52	25.88	2.72

The transport associated with the tides may be computed as follows. Assume that the tidal prism of the inner inlet fills on flood tides with water from the inflowing layer and subsequently drains into the inlet's outflowing layer. Taking the intertidal volume between the average highest daily stand of the tide and the average lowest tide (i.e., between MHHW and MLLW; Table 3), divided by the length of a tidal day, yields 289 m^3/sec. Uncertainties in the tidally-derived transport arise because the boundary for the inner inlet is imprecise, and some ebb water undoubtedly returns (refluxes) on flood tides to the inner inlet.

While evaluating the flushing potential of the inner inlet, Albertson et al. (1998) estimated the upwelling where URS (1986) previously noted upwelling in contours of ammonium, nitrate, and nitrite. Using simplified box models and environmental data (Capitol Lake discharge, inlet salinities) for spring through fall of three years (1992, 1993, 1994), Albertson et al. (1998) estimated an annual average upwelling transport of 313 m^3/sec.

Despite the uncertainties, the agreement of the tidal pumping estimate with those from measured currents and the box and hydrodynamic models points to tidal pumping, which rapidly uplifts and transfers water from the inlet's inflowing to its outflowing layer.

Discussion

Computers and hydrodynamic modeling have evolved rapidly in the past few years. Three-dimensional models with fine spatial meshes and small time steps are now routinely applied to estuarine circulation. Distilling this body of experience, Jian Wu et al. (1998) write: "One fundamental principle that has been learned is that the water quality within a water body can only be modeled to the detail with which the hydrodynamics of that water body is known." Careful 3-D modeling of Budd Inlet has clearly verified the lateral separation of the inlet's inflowing and outflowing currents as observed with the current meters.

Lacking a 3-D model and comprehensive current measurements, previous studies estimated water transport in the inlet by applying laterally-averaged box models to hydrologic (river discharge) and hydrographic (salinity) data. Because the previous data were collected mostly at mid-channel or did not adequately represent the laterally separated flow layers, the resulting transports varied widely up to 2,000 m^3/sec compared with the present estimate of approximately 300 m^3/sec (URS Corporation, 1986).

The present results suggest that tidal pumping maintains a vigorous circulation year-round in Budd Inlet, secondarily controlled by discharge from Capitol Lake. Water properties (temperature, salinity, density, oxygen), reflecting the pump, change primarily across the inlet rather than down inlet as is typical of estuaries because the pump draws water from one side of the inlet and expels it along the other side.

Acknowledgements

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Inlet Hydrodynamics under an Intermittent Discharge: Capitol Lake and its Impact on Budd Inlet

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Introduction

West Bay is an area of critical water quality concern in Budd Inlet, chronically exhibiting oxygen levels that approach hypoxic conditions during late summer and fall (Ebbesmeyer et al., 1998). Depressed oxygen levels may be due to nutrient loading, circulation, or a combination of both. Cox et al. (1998) quantified nutrient loadings to Budd Inlet. This paper investigates how the operation of Capitol Lake influences the circulation of West Bay, and whether or not this circulation may be contributing to near-bottom, depressed oxygen levels in West Bay.

Capitol Lake

The present site of Capitol Lake was once an estuary where fresh water from the Deschutes River[i] met the salt waters of Budd Inlet. In 1951, a dam was built under Olympia, Washington's 5th Avenue bridge resulting in the formation of a shallow[ii] 270-acre lake. The lake is part of the Capitol campus and is operated by the Washington State Department of General Administration. The lake was originally constructed to serve as a reflection pond for the state capitol. Today however, the lake has become a recreational haven for joggers and picnickers, and a major rearing area for chinook salmon[iii].

The Deschutes River drains into Capitol Lake from the south[iv]. Two radial gates located in the dam structure regulate releases. Gate operation is automated by a METASYS control system. The operational strategy is to maintain Capitol Lake at a desired level[v]. When the lake rises above the desired level, the gates open as long as the head differential between the lake and the tide is at least one foot. Should the lake drop below the desired level or the lake/tide differential drop below one foot, the gates automatically begin to close. Selected flow statistics for the period from November 1996–August 1997 are presented in Table 1.

Table 1. Capitol Lake Flow Statistics

Description	Flow Study Period 11/5/96 – 9/30/97	Winter 11/5/96 – 1/31/97	Summer 7/1/96 – 9/30/97
Average flow	666 cfs (18.9 m^3/sec)	1,153 cfs (32.7 m^3/sec)	197 cfs (5.6 m^3/sec)
Peak flow	16,184 cfs[vi] (458.3 m^3/sec)	16,184 cfs[vii] (458.3 m^3/sec)	7,110 cfs (201.4 m^3/sec)
Average flow with the gates open	1,374 cfs (38.9 m^3/sec)	1,905 cfs (54 m^3/sec)	692 cfs (19.6 m^3/sec)
Percentage of time gates open	50 %	60 %	21 %
Average length of time gates open	2.7 hours	4.4 hours	3.2 hours
Gate opening frequency	4.3 times/day	3.3 times/day	1.6 times/day

West Bay

West Bay is the southernmost embayment of Puget Sound. Table 2 lists selected physical characteristics of the bay. An important feature of West Bay is a dredged ship canal that runs along the

axis of the bay. At its southernmost end, the ship canal widens into the turning basin as shown in Figure 1. The turning basin is approximately 10 ft (3.1 m) deeper than the ship canal, reaching a maximum depth of approximately 40 feet (12.2 m).

Table 2. West Bay Physical Characteristics

	Non-Metric Units	Metric Units
West Bay length from mouth to Capitol Lake	5500 ft	1.7 km
Width at mouth	2000 ft	0.6 km
Maximum depth	40 ft	12.2 m
Volume at[viii]:		
Mean High Water (MHHW)	~ 3.0×10^8 ft^3	~ 8.6×10^6 m^3
Mean Lower Low Water (MLLW)	~ 1.6×10^6 ft^3	~ 4.6×10^6 m^3

Table 3. Deployment Data

Deployment No.	Water Depth Relative to MLLW (m)	Latitude 47^o N (minutes)	Longitude 122^o W (minutes)	Deployment Date	Retrieval Date
1	10.36	3.086	54.367	10/30/96	12/13/96
6	8.53	3.130	54.400	7/18/97	8/13/97
7	8.84	3.074	54.384	8/14/97	10/3/97
8	8.95	3.100	54.491	11/26/97	1/8/98
9	8.56	3.107	54.477	1/8/98	2/20/98

Methods

Currents

West Bay currents were measured using an Acoustic Doppler Current Profiler (ADCP). Through a series of nine continuous deployments, currents were measured from October 30, 1996–February 20, 1998. Current speed and direction were averaged for two-minute intervals every 15 minutes at one-meter depth intervals. Current meter malfunctions occurred during four deployments (deployments 2, 3, 4, and 5), rendering unrecoverable data. Deployment information from the other measurement periods is presented in Table 3. The approximate locations of the ADCP deployments are shown in Figure 1.

Capitol Lake Flows

The Capitol Lake gates lack hydraulic features to allow direct measurement of flow. To overcome this limitation, a level-pool routing approach was adopted for estimating discharge (LOTT Wastewater Resource Management Plan, scheduled completion summer 1998). This approach balances inflows and outflows with storage. A trapezoidal solution was employed to iteratively solve the conservation of mass equation. Inflows consisted of flows received from the Deschutes River and Percival Creek. Deschutes River flows were obtained from USGS gauging station 12080010 located approximately 0.5 miles[ix] south of Capitol Lake. Percival Creek flows were estimated with The Precipitation Routing to Stream Model (TPRSM), a continuous hydrologic model which tracks antecedent moisture conditions (LOTT Wastewater Resource Management Plan, scheduled completion summer 1998).

Outflow and storage were calculated in two different ways. The first method relied on lake level data recorded by the METASYS control system. Lake level data was converted to storage with the stage-storage relationship. Outflow was calculated from the solution of the mass conservation equations. The second method employed a calibrated hydraulic model to compute outflow. Storage was calculated from the solution of the mass conservation equations. The second approach was implemented when METASYS control system data was unavailable.

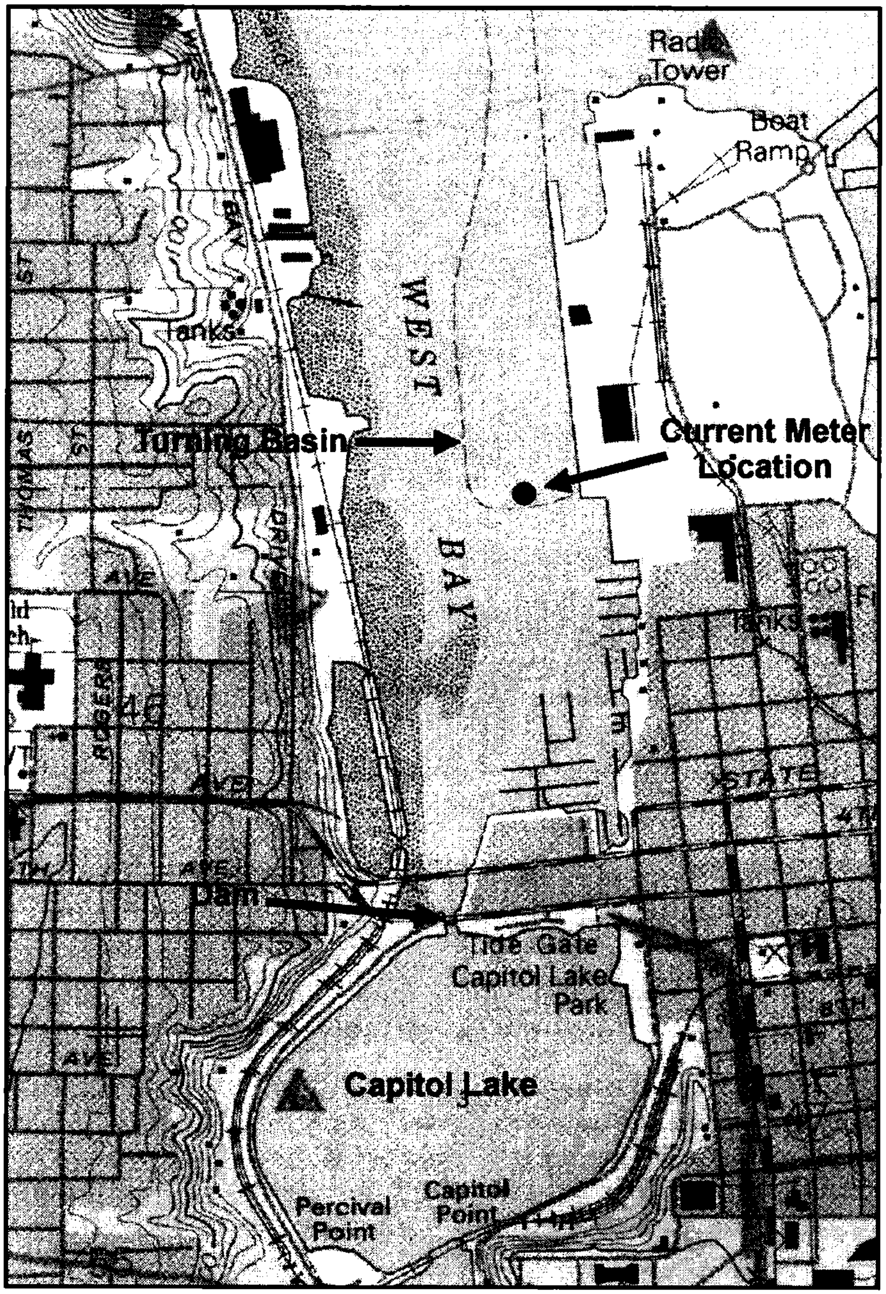

Figure 1. West Bay

Discussion

West Bay currents exhibit a pronounced reaction to discharge from Capitol Lake. Wintertime ADCP deployments revealed a strong, northward-moving, freshwater lens at the surface during releases. During the summertime, the fresh water lens appears to be strongest approximately two meters below the surface. The influence of fresh water releases was typically evident at the ADCP site within 15–30 minutes after gate openings. Velocity structures associated with fresh water releases diminished within a similar time frame. Snapshots in time of the north-south velocity structure during a large release are shown in Figure 2.

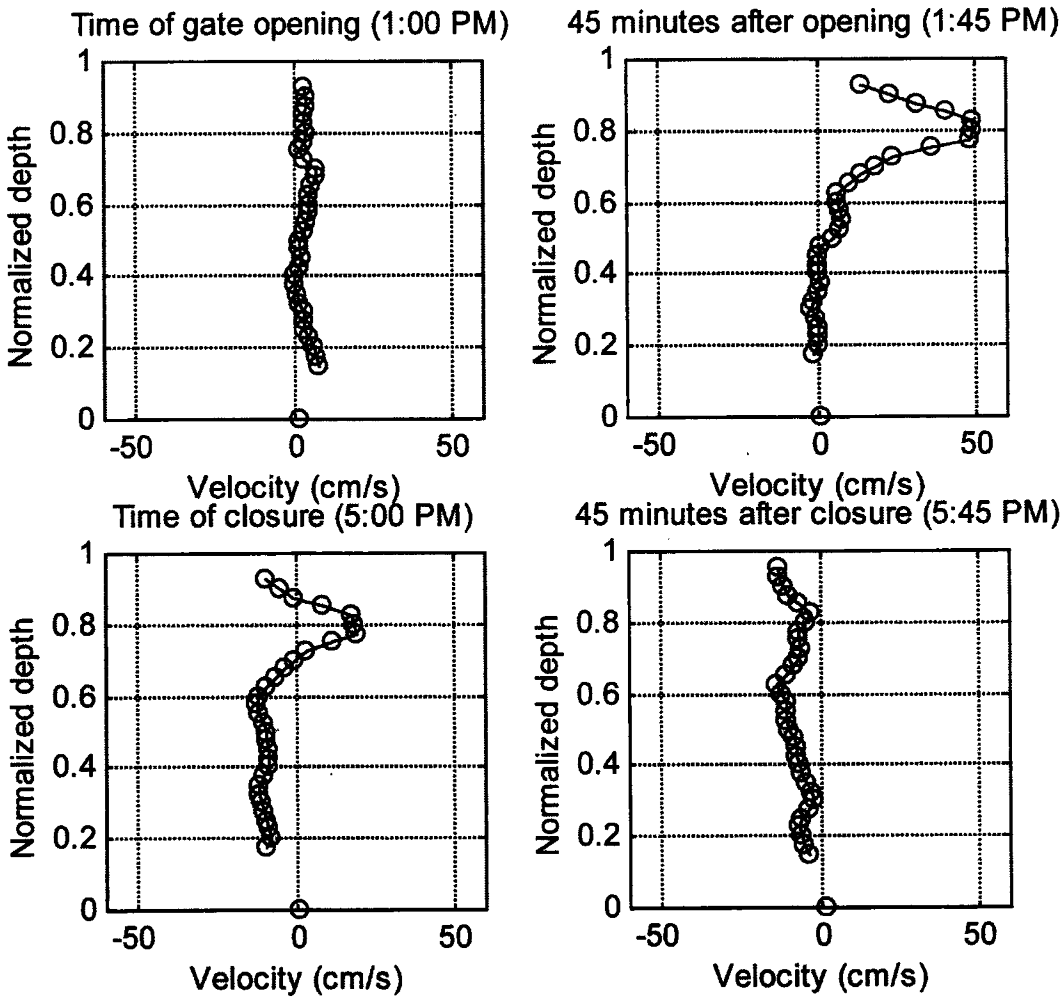

Figure 2. Time-series of north-south velocity during Capitol Lake discharge on July 25, 1997

West Bay salinity concentrations near the sea surface exhibited a strong depression during and after Capitol Lake releases (Figure 3). The background salinity is approximately 25 ppt. During the release concentrations dropped to a minimum of 7 ppt, a reduction of over 70%. Post-release depression of the salinity profile is due to back-washing of fresh water during the flood tide. Flows estimated with the level-pool routing technique correspond well with the salinity profile.

North-south wintertime currents in West Bay exhibit a typical estuarine profile (Figure 4). East-west currents are presented in Figure 5. The vertical scale has been normalized by the water surface elevation. The velocity component near the surface is a result of fresh water flowing northward due to buoyancy and the significant momentum realized in the exchange of potemtial energy for velocity head during lake releases. Strong surface currents induce a return flow at about 0.8D–0.9D, where D is the normalized depth. As would be expected, stronger return flows are correlated with higher average flows from Capitol Lake. The return flow from November 7 – November 14 is barely discernible. During this time Capitol Lake flows averaged 212 cfs (6 m^3/sec). However, in late November and early December after flows increased approximately six times, the return flow became a strong feature.

Wintertime lake releases do not seem to significantly affect north-south currents below 0.5D. Below half the water depth the currents are relatively uniform and almost completely in the southward direction. The one exception is the December 5–December 12 data set which exhibits a weak northward component at about 0.3D. Typical currents in the bottom half of the water column are southward at 1–2 cm/sec.

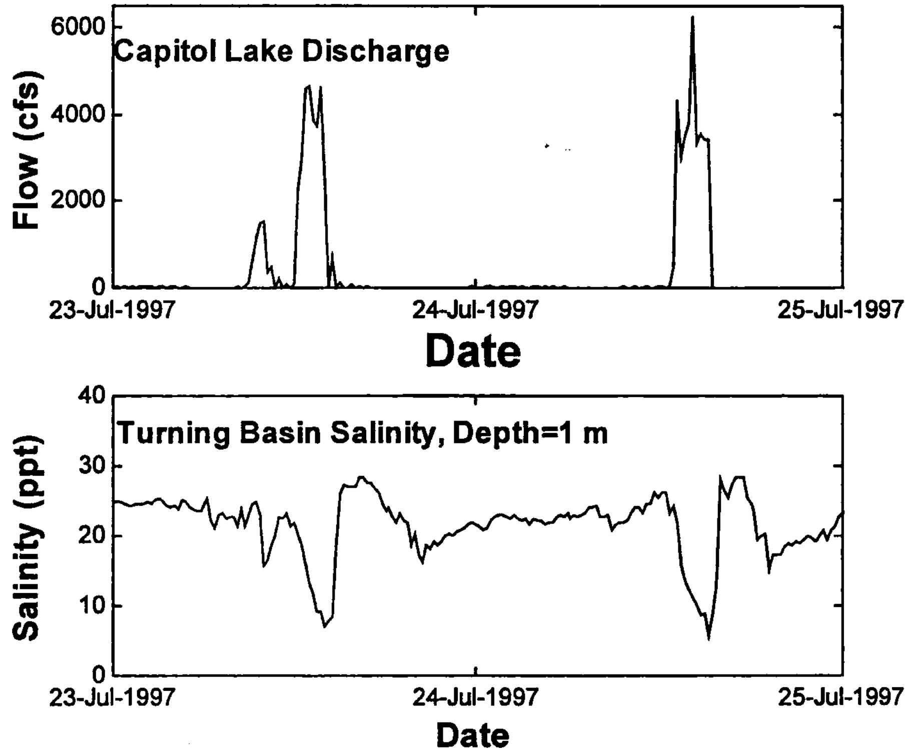

Figure 3. Salinity depression in West Bay during Capitol Lake discharge

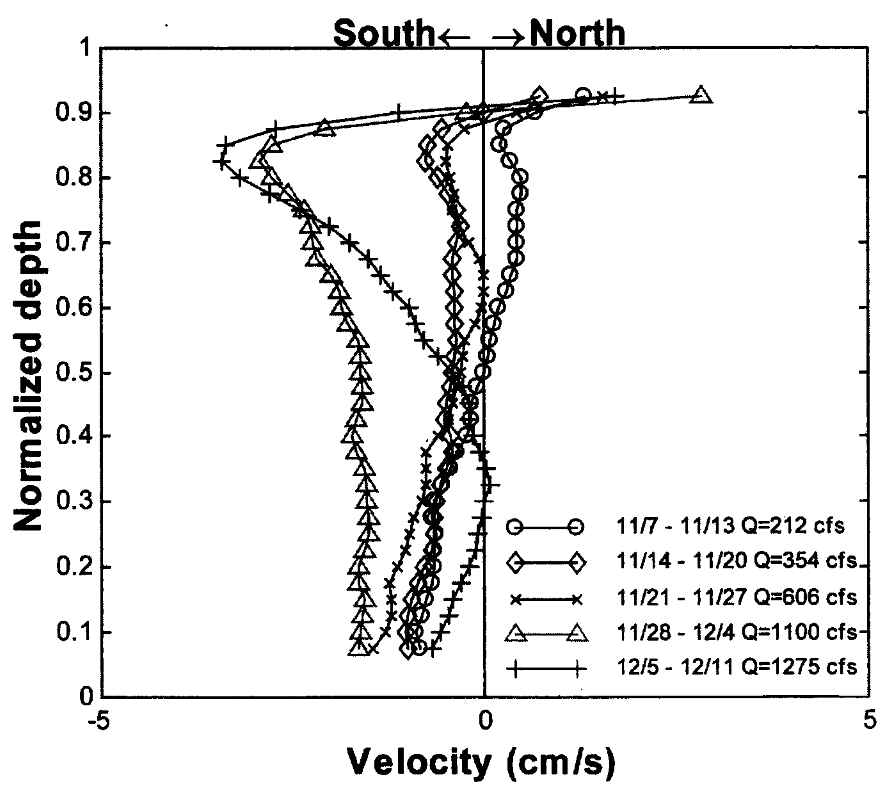

Figure 4. Wintertime seven-day tidally averaged N-S currents

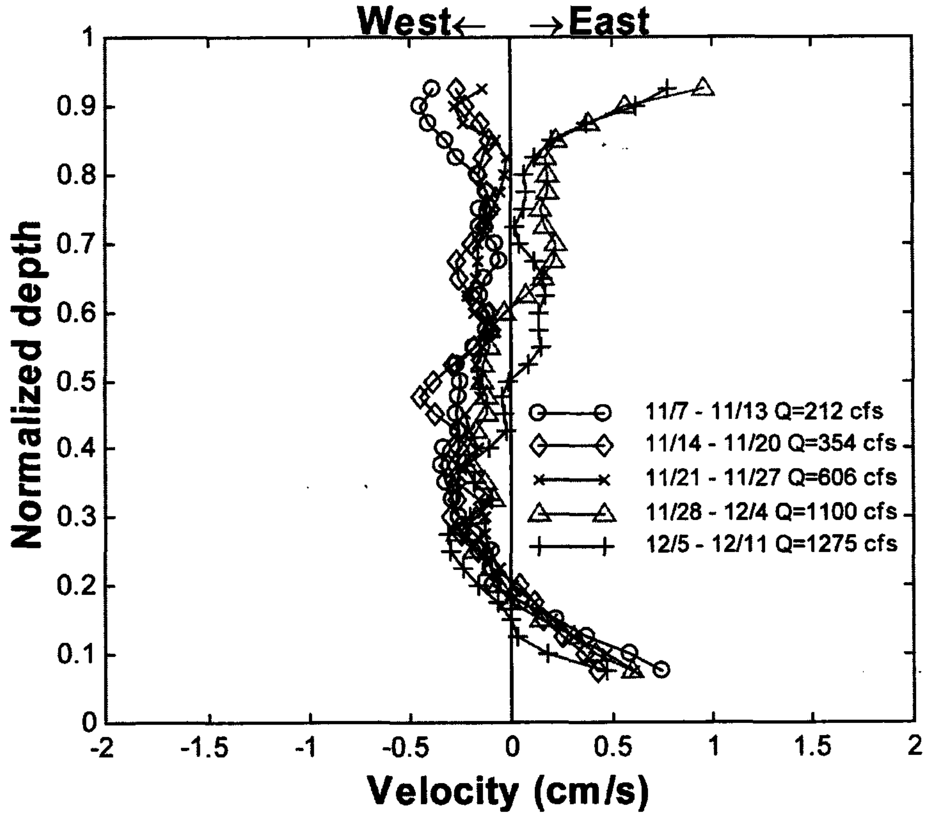

Figure 5. Wintertime seven-day tidally averaged E-W currents

Each year Capitol Lake is partially emptied and then refilled during the summer. Collectively referred to as the drawdown event, it subjects West Bay to one extreme and then the other. The 1997 drawdown occurred from July 22–July 30. During this period the lake was lowered from a normal summertime level of 6.4 ft above mean sea level (MSL) to 3.0 ft below mean sea level over a four-day period. All told, over 750 acre-feet of fresh water were released to West Bay. After the lake level dropped to –3.0 ft MSL, it was refilled to –1.0 ft MSL with salt water. For the next five days, the gates remained closed while the lake was refilled by the Deschutes River to a normal level, at which time normal operation resumed (Washington State Department of Fisheries, 1997).

The drawdown period provides a unique opportunity to observe currents under the influence of strong fresh water releases followed by a period of minimal freshwater release. While the lake refills, West Bay ceases to be an active estuary for several days. North-south currents during and after the drawdown period are shown in Figure 6. The velocity structure during this deployment is not as easily understood as the wintertime structure. Unlike the wintertime two-layer structure, the summer structure appears to have as many as four layers. At this time some of the features are poorly understood. The near-surface velocity approaches zero while the strongest northward velocity is submerged. In addition, a strong southward jet was repeatedly observed periodically around 0.7D throughout the period. This jet is most clearly visible during the period when the gates were closed (July 26–July 30), removing Capitol Lake from the list of potential influences. The near-bottom velocity is approximately 1 cm/sec in the northward direction. This relatively fast velocity (approximately 1 km/day) out of the West Bay is not suggestive of a stagnant body of water. Moreover, it suggests that West Bay approaches hypoxic conditions in spite of significant flushing; however more needs to be known about the cross-channel current variation before any conclusions can be drawn.

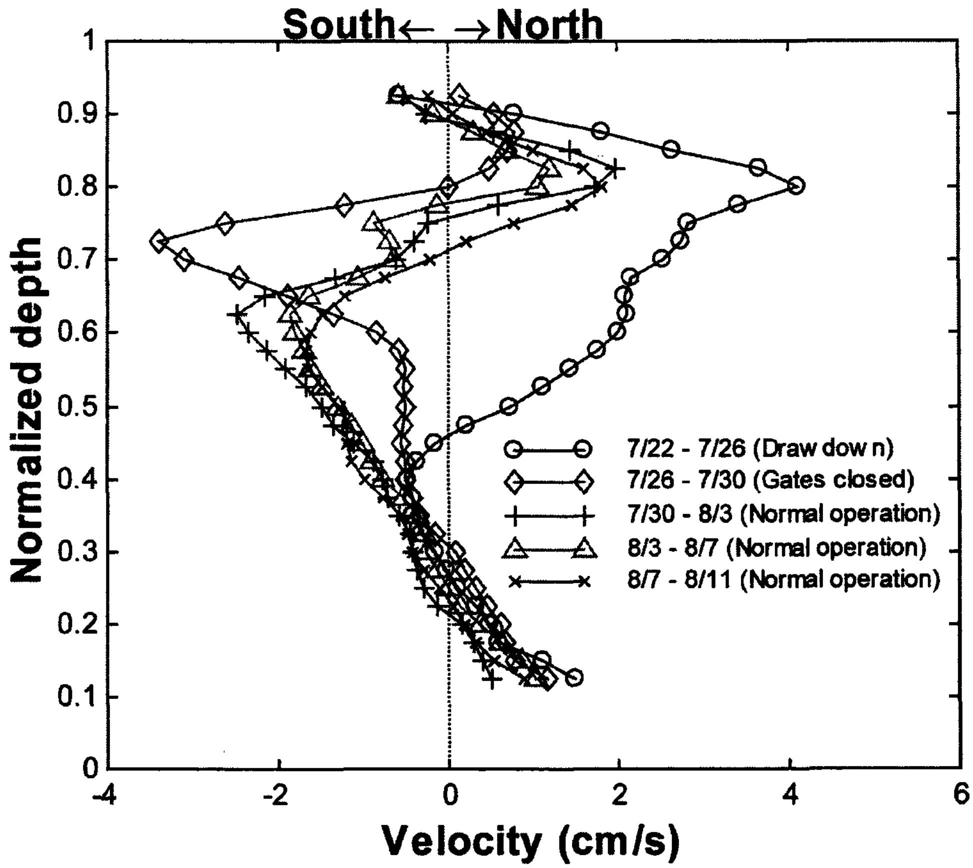

Figure 6. Drawdown period four-day tidally averaged N-S currents

The two most important factors driving West Bay currents are tides and Capitol Lake releases. In order to decompose the freshwater current component, currents under tidal action (July 26–July 30) were subtracted from currents during gate normal operation (July 30–August 11). Tidal currents were also subtracted from currents during lake drawdown (July 22–July 26). The resulting fresh water constituents are shown in Figure 7. Below 0.4D, the influence of Capitol Lake, even during extreme events, has minimal effect on north-south currents.

Acknowledgements

The authors would like to thank the LOTT Partners and Tim Crone of Evans-Hamilton for his valuable assistance in preparing figures.

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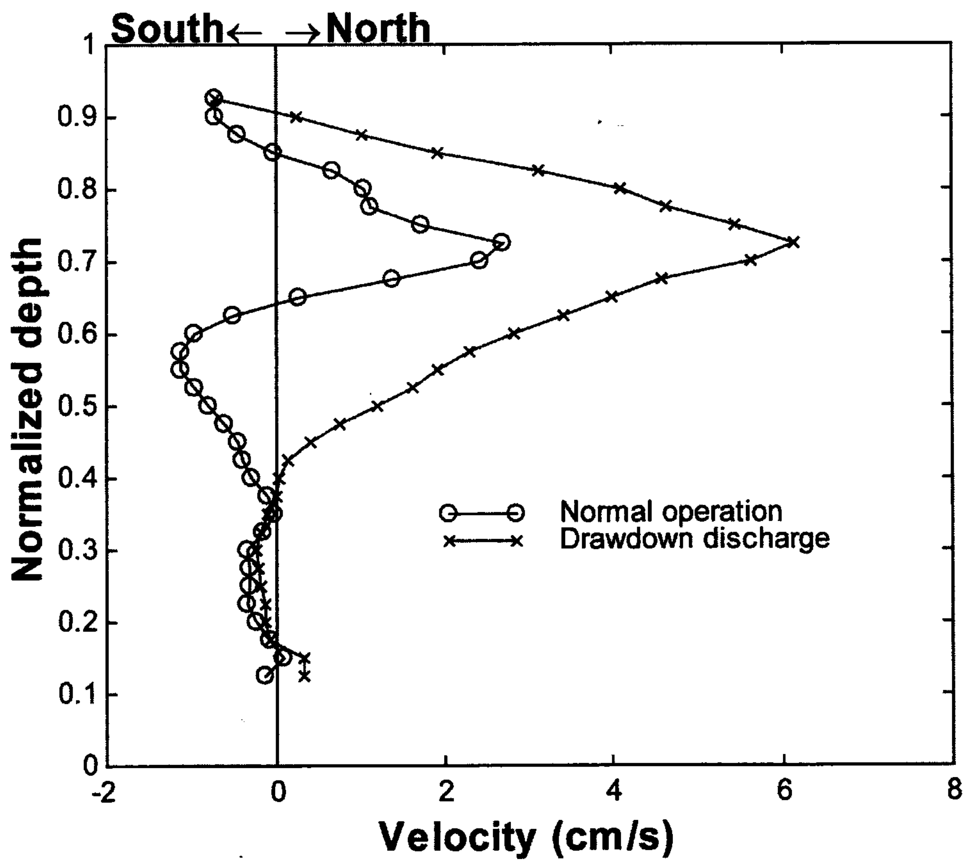

Figure 7. Capitol Lake-Induced N-S Currents

Washington State Department of Fisheries. Hydraulic Project Approval, July 18, 1997.

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ii Mean flow based on 34 years of records at USGS gauging station 12079000 is 530 cfs (15 m^3/sec).
ii Average water depth is 6.5 feet.
iii The Washington Department of Fish and Wildlife places approximately 5 million fingerlings in the lake each year (The Olympian, October 13, 1997).
iv Though small compared to the Deschutes River, other sources do contribute flows to the lake. Of these, Percival Creek is the largest (mean flow based on 2 years of records from USGS gauging stations 12078720 and 1278730 is 1.2 m^3/sec). Rainfall, groundwater discharge, and urban runoff are other contributors.
v Normal wintertime lake level is 5.8 ft above Mean Sea Level (MSL). Normal summertime lake level is 6.4 ft above MSL. (C. Eikard, personal communication).
vi Occurred December 30, 1996.
vii Occurred December 30, 1996.
viii Albertson et al., 1998
ix River travel distance.

Seasonal and Interannual Variations of Residence (Flushing) Time in the West Bay of Budd Inlet

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Matt Davis
Brown and Caldwell

Introduction

We were interested in the seasonal and interannual changes in the flushing time of the West Bay in Budd Inlet due to the low levels of dissolved oxygen (DO) often found near the bottom of the turning basin in the late summer. The Washington State Dept. of Ecology took hydrographic data in the inlet during 1992–4 (Figure 1). We constructed a two-layer box model (Figure 2) and used conservation of mass and salt to calculate overall transports between boxes using these data.

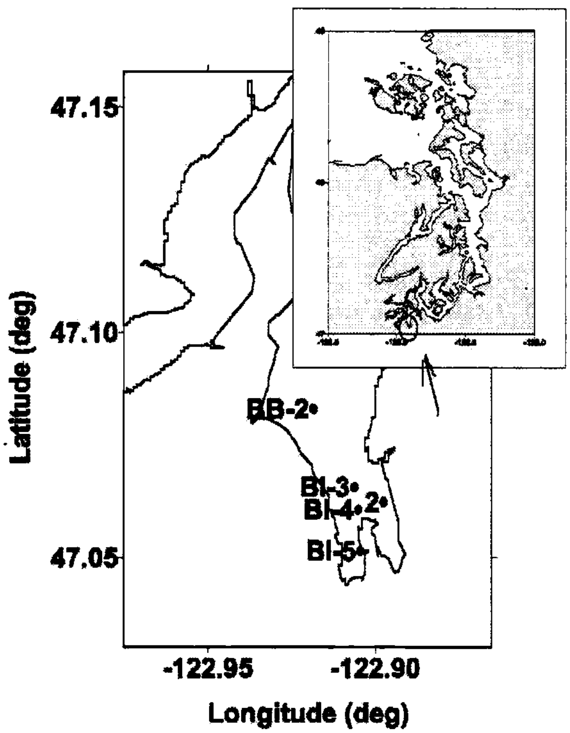


Figure 1. Station locations for box model.

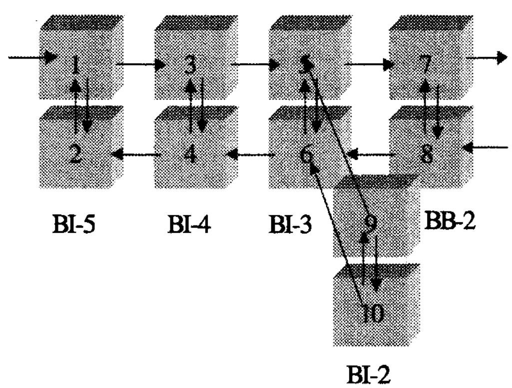


Figure 2. Budd Inlet box model.

Methods

A Volumetric Argument

The Lacey Olympia Tumwater Thurston (LOTT) wastewater treatment plant (WWTP) has a mean summer discharge of about 9 mgd (34,000 m^3/d). The typical outflow from Capital Lake is 475,000 m^3/d; an extreme flow condition is about 1.5×10^6 m^3/d. Assuming that all waters mix completely, point "A" (Figure 3, 0.2 km from head) is the location at which the fresh water outflow (river plus LOTT) is

equal to the volume of the tidal exchange (top - bottom curve) under typical conditions. This is the distance from the head of the inlet where 50% dilution of fresh water outflow with saltwater occurs in one day. Consequently, the turning basin, which is approximately 0.6 km from the head of the inlet (point "B"), should flush in about one-third of a day based on this tidal advection and thorough mixing. In the extreme flow condition, this flushing time increases to about one day at the turning basin.

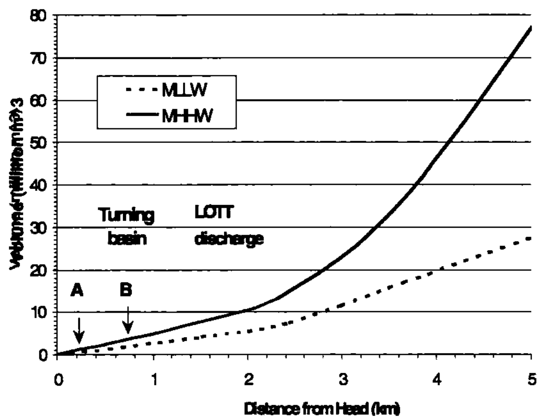


Figure 3. Water volume vs. distance from the head of Budd Inlet at Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW).

Box Models and the Knudsen Relation

Unlike the scenario above, we know the actual state of mixing in an estuary is apt to be less than thorough. In the absence of current meter data, the box model solution is uniquely determined and reduces to the Knudsen relationship (Knudsen, 1900) solution at any single location. The box model, however, allows determinations of both horizontal and vertical transports, as well as inclusion of multiple freshwater sources at different locations. Ideally, station locations should be chosen with a box model in mind, if that is to be the purpose. We, however, chose from available monitoring stations and accepted or rejected them as suitable for our purpose. Although station BI-3 (Figure 1) was shallow, 9 m east of the main channel, it nevertheless received a good freshwater signal and was included in the model. However, fluxes into and out of the bottom box at this location (box 6) should be ignored.

We made the following assumptions (justifications not shown):

- Steady-state (no change with time)
- Two-layer tidally averaged flow
- Only freshwater sources: Capital Lake (Deschutes), Moxlie & LOTT WWTP
- Each box is homogeneous
- Negligible evaporation/precipitation

Only surveys that included both high and low tide transects were used, and those data were averaged from the surface down (i.e., salinities from the top 2.5 m from the low tide was averaged with the top 2.5 m from the high tide). Without current meter data we could not establish the level of "no motion" and instead used the average depth of the halocline, 2.5 m, as the separation depth between top and bottom boxes in the model (Figure 4).

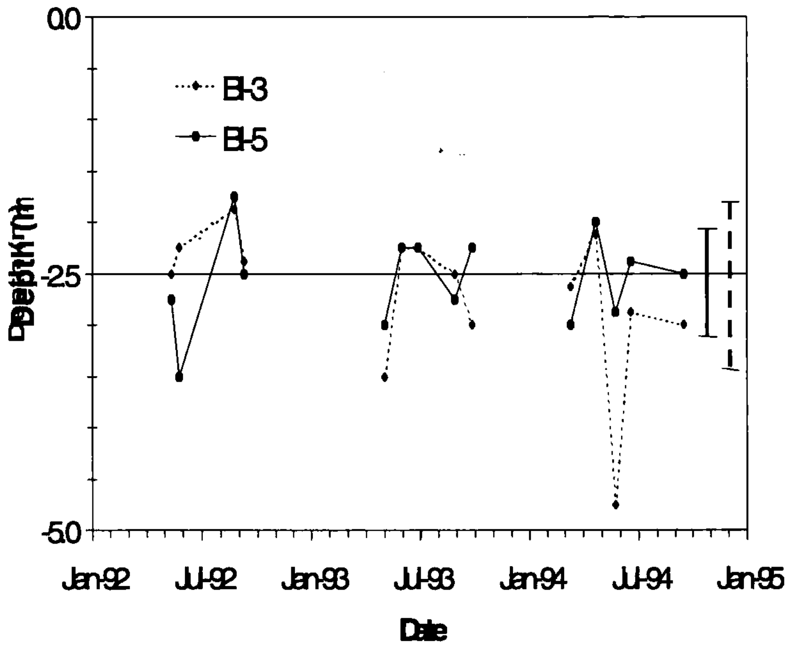


Figure 4. Halocline depths at two stations.

River flows, which were not at all steady, were smoothed forward and backward half a sidereal day. On the average, along-channel vertical transects of salinity showed the typical estuarine flow pattern with a slight downstream shift of the freshwater maximum (Figure 5). Thus in our box model results, the flows from the bottom, innermost box may be inaccurate.

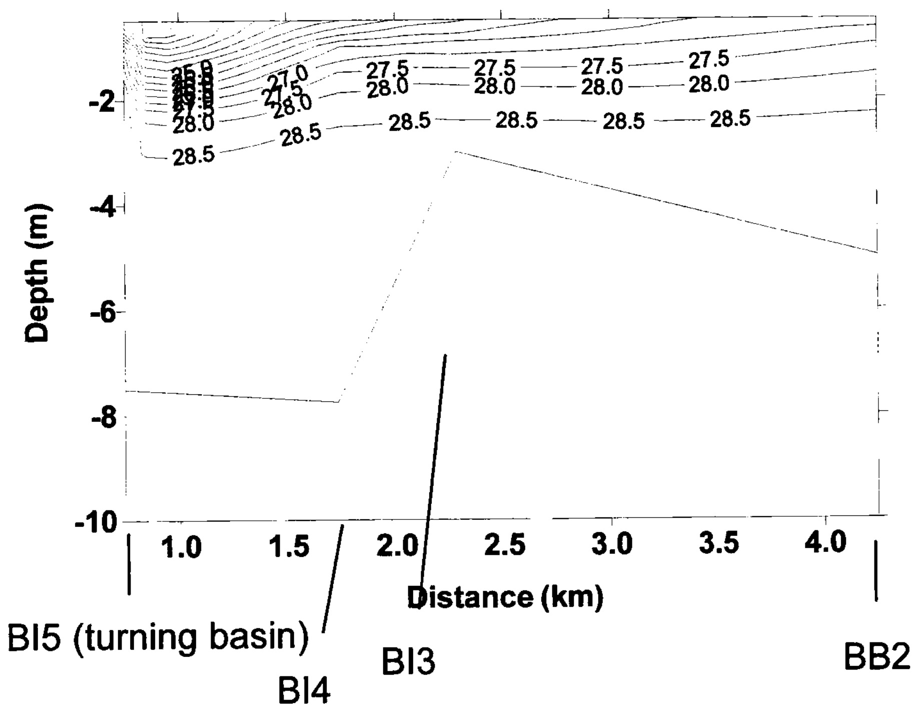
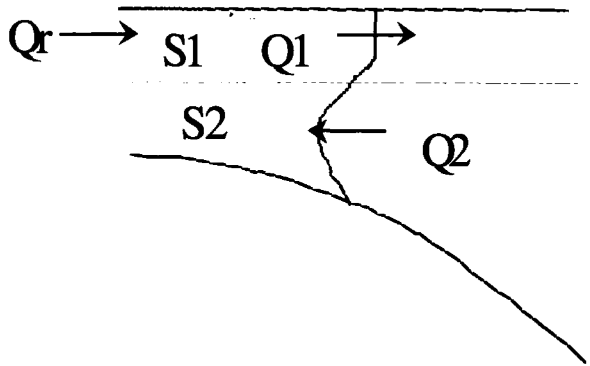


Figure 5. Vertical profile of mean salinity (psu) for all surveys included in the model Knudsen relation in the turning basin.

Stratification that persists with (seasonal) reductions of freshwater discharge is indicative of poor flushing conditions. The Knudsen relation quantifies this at one station as:

$$\Delta S = S_2 - S_1$$
$$\tau_1 = V_1 \, \Delta S \,/\, Qr \, S_2$$
$$\tau_2 = V_2 \, \Delta S \,/\, Qr \, S_1$$



where:

- Qr is the freshwater inflow
- S_1 & Q_1, S_2 & Q_2 are the surface and bottom salinities and flows, respectively
- V_1 & V_2 are the surface and bottom box volumes
- and τ_1 & τ_2 are the derived residence times.

In order to see the flows between stations, we constructed a box model whose solution is found by solving the matrix in Figure 6.

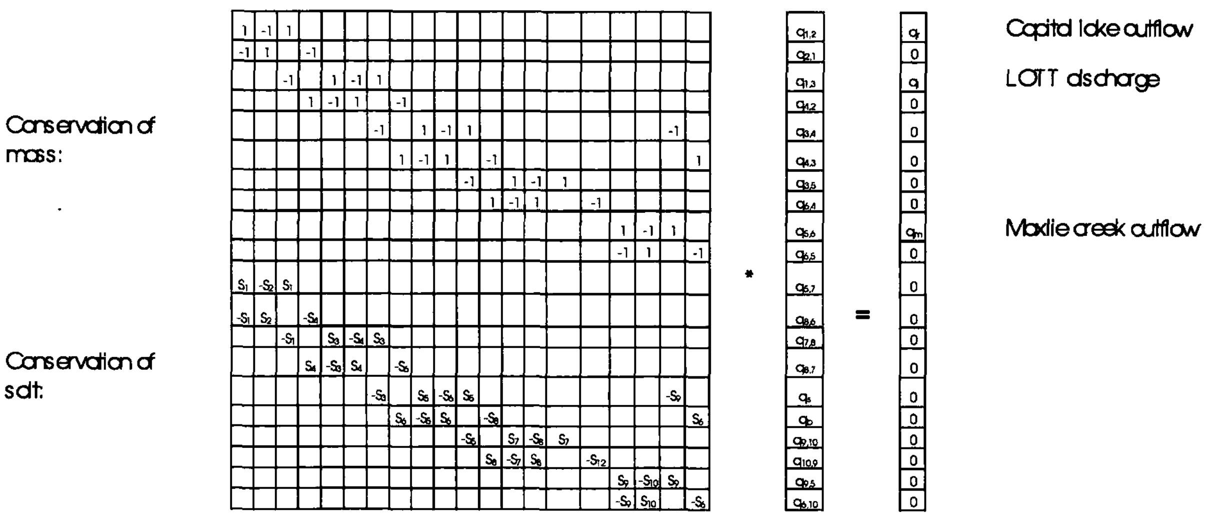


Figure 6. The box model (q_s = surface flow out of Box 7, q_b = bottom flow into Box 8).

Results

From the Knudsen relation, we find that despite seasonal downturns in freshwater inflow (Qr), the stratification (ΔS) remains fairly high, indicating longer residence times in the turning basin (Figure 7). The largest residence time was nearly four days on 19 September 1994 in the bottom of the turning basin.

From the box model, we find that flushing in the turning basin (Box 2) usually occurs in less than

one day. The seasonal pattern is consistent for all the stations, with the highest residence times occurring in the late summer. The interannual variation shows the highest residence times occurring in the fall of 1994 (Figure 8). This corresponds with when the lowest DO concentrations were observed during the original study (Eisner and Newton, 1997)$_{17.6}$

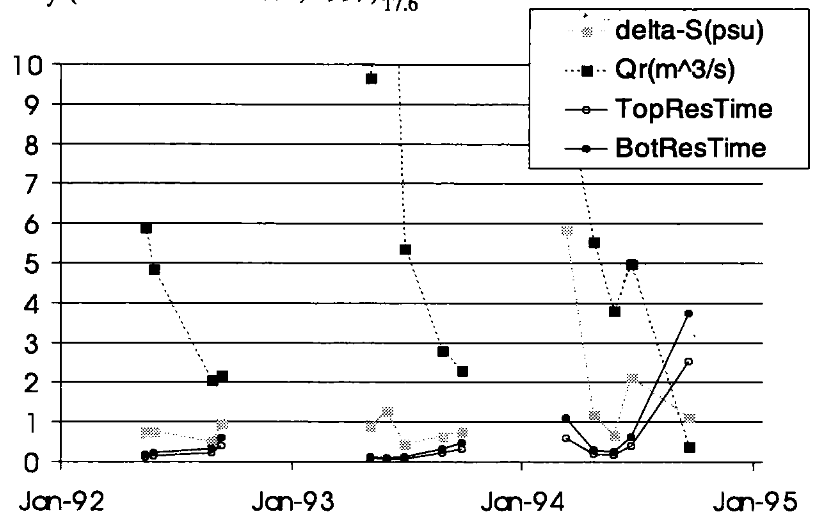


Figure 7. Knudsen relation results in the turning basin (Station BI-5, model Box 2).

Transports and currents in the East Bay are particularly low, but so is the volume. West bay flows were approximately 10 cm/sec in the model, which are comparable to those measured by ADCP (Davis et al., in press). Upwelling was greatest in the box model around station BB-2 at about 310 m^3/sec (Figure 7).

Discussion

At times when fresh water inputs are greatest, the box model predicts flushing times of less than a day; this is consistent with the results from the volumetric argument which assumes thorough mixing. At times when there is less mixing, mainly in the late summer, the residence times increase. The Knudsen relation and the box model solutions have the same seasonal and annual patterns.

The increase in residence times occurs at the same time of the year as the end of the growing season for the inlet, contributing to depressed levels in the dissolved oxygen (DO) concentrations. The highest chlorophyll *a* concentrations occur in the central bay, near station BB-2 (Eisner and Newton, 1997), which is possibly related to the gyre circulation (Ebbesmeyer, this volume). This results in large amounts of carbon falling into the bottom waters and decaying, consuming oxygen in the process, such that the water moving into the turning basin (BI-5) would already have low DO. Coupling this with seasonally high residence times could explain why we find near-hypoxic conditions in the turning basin in the late summer and early fall. The correspondence of the lowest DO concentrations occurring when residence times were greatest (fall, 1994) is consistent with this understanding.

Possible physical mechanisms to account for the seasonal variations in flushing include: lower tidal forcing near the equinox at the end of September (pers. comm., H. Mojfeld, NOAA PMEL), seasonal changes in wind patterns and resultant gyres which may retain water in the basin. The year-to-year variability is more likely linked to changes in weather patterns and river flow (Albertson, 1996).

Acknowledgments

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(University of Washington), and Jan Newton (Dept. Ecology) for their review and feedback.

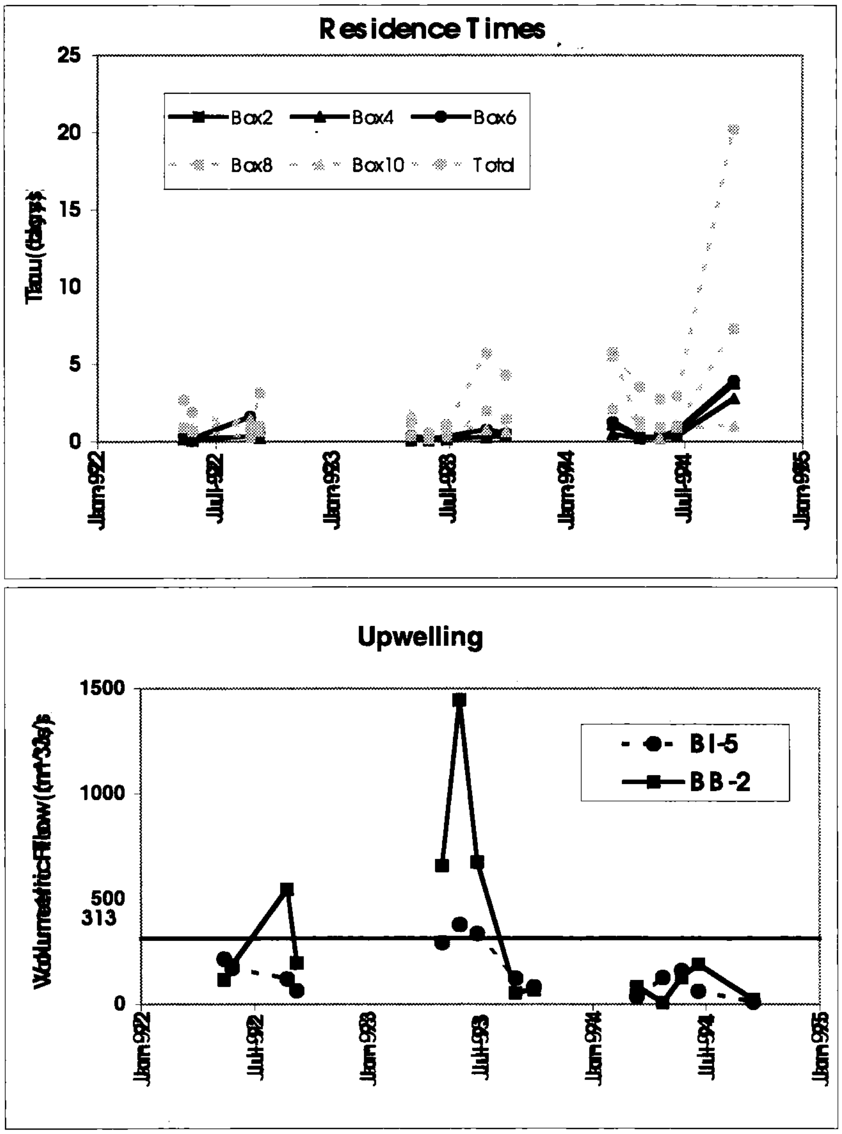

Figure 8. Box model outputs of residence time and vertical transport. The solid line represents a mean upwelling rate of 313 m^3/sec.

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Seasonal Variations of Dissolved Inorganic Nitrogen in Budd Inlet, Washington

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Introduction

The growth experienced by the city of Olympia, Washington and surrounding communities has caused increased demand on existing wastewater treatment facilities. Increased disposal of waste water into Budd Inlet during the winter months from the Lacey-Olympia-Tumwater-Thurston County Wastewater Treatment Plant (LOTT) has been proposed as a partial solution to this difficulty. A 13-month intensive field measurement effort was made to determine the feasibility of this option (Budd Inlet Scientific Study Final Report, 1998). One tool that was created to help assist in this decision was a model that incorporated both water quality and circulation information.

The major historical water quality problem in Budd Inlet has been the development of low dissolved oxygen (DO) concentrations in the lower portions of the water column during late summer and into fall. This condition occurs in the head of the inlet and occasionally extends into the central portion of the inlet as well. Earlier studies attributed low DO levels to a number of factors, including:

1) water entering Budd Inlet from Puget Sound that contained lower DO;
2) a strong thermocline that caused severe vertical stratification;
3) excess nutrients that allowed large plankton blooms to occur; and
4) decay of plankton blooms that increased the demand for DO (WDOE, 1997).

WDOE (1997) documented the dissolved inorganic nutrients limiting plankton growth in Budd Inlet as ammonia, nitrate, and nitrite. Regulation of these nutrients was viewed as the key to controlling plankton blooms and the subsequent low DO conditions. As the most easily controlled input of these nutrients, LOTT was required to implement a dissolved inorganic nitrogen (DIN) removal process, which has been active from at least 1 April to 31 October annually since 1994. During the summer of 1994, WDOE (1997) documented that DIN concentrations in both LOTT effluent and in Budd Inlet were greatly reduced compared to the summers of 1992 and 1993. However, LOTT's contribution of DIN to the whole inlet was not assessed at the time.

To place in perspective the major sources and sinks of dissolved inorganic nitrogen (DIN) to Budd Inlet, the flux of DIN into and out of the inlet was computed for both the whole and inner inlet to form nutrient budgets (Figure 1). The nutrient budgets integrated many of the measurements conducted during the Budd Inlet Scientific Study, including those from current meters, river discharge, sediment fluxes, precipitation, wastewater treatment plants (WWTPs), inlet surveys, and primary productivity experiments.

For this analysis, the pool of DIN was considered to be the DIN residing in the marine waters within either the whole or inner inlet. Sources that released DIN into the inlet's waters include fresh water (rivers, streams, creeks, and rainfall), sewage treatment plant discharges (also fresh water), inflowing marine waters from Puget Sound, and sediments.

The sinks of DIN included marine water exiting to Puget Sound, the sediments, and phytoplankton uptake of DIN. Primary productivity experiments measured the DIN uptake due to phytoplankton growth. These nutrients can then be released to the water column upon cell lysing or become part of the sediment when the cells die and sink to the sea floor. The DIN loss terms were calculated in two ways, including and excluding primary productivity in order to gain a better perspective on the role phytoplankton play in the nutrient dynamics within the inlet.

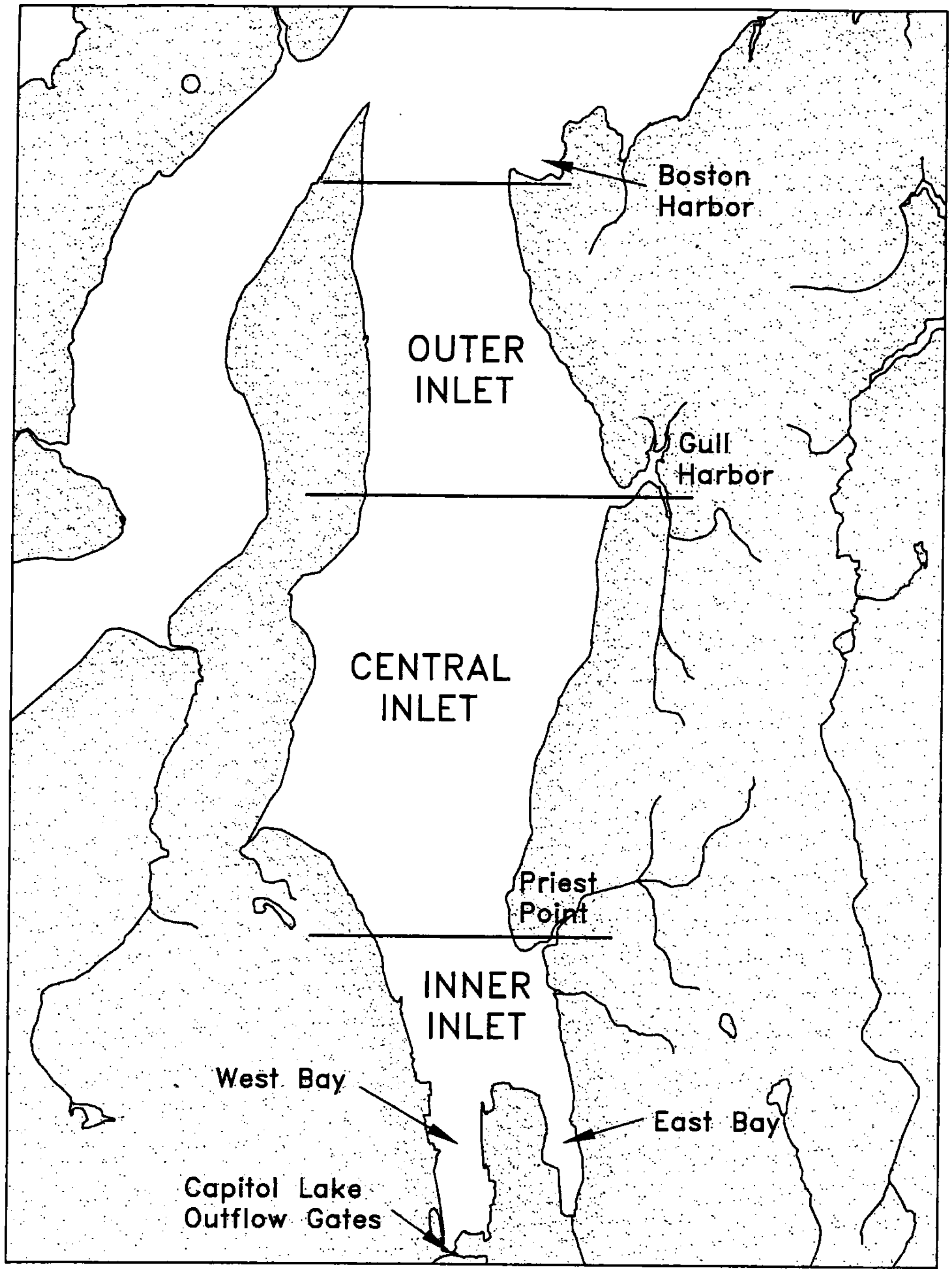


Figure 1. Budd Inlet, Washington methods.

Inputs of DIN were based on field measurements from many different facets of the study. Inlet, benthic, and shoreline surveys occurred twice per month over a 13-month period (Figure 2). In addition, moored meters measured water conditions and movements continuously over the study period (Figure 2). Wastewater treatment plant and freshwater DIN loadings were calculated from shoreline survey DIN samples and daily flow rates computed using a freshwater flow model. Puget Sound DIN loadings were computed using DIN concentrations measured in the incoming marine water and monthly net transport values obtained from the current meters (Ebbesmeyer and Coomes, 1998). DIN from the sediments were determined from benthic flux measurements and the bottom surface area at mean lower low water (MLLW) (Uhlenhopp and Devol, 1998).

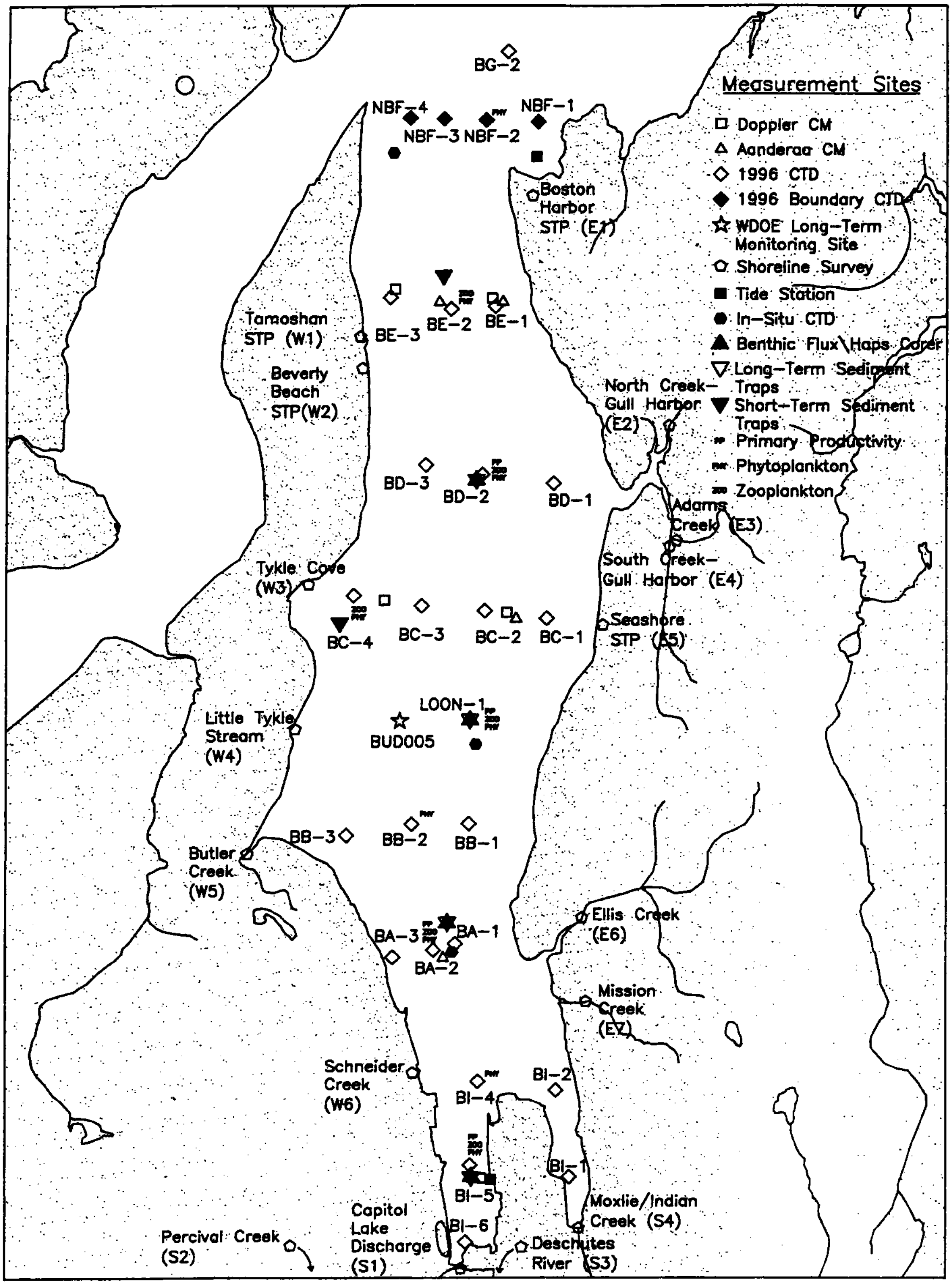


Figure 2. Budd Inlet Scientific Study measurement stations.

Outputs of DIN were computed in a similar manner to the inputs. Puget Sound DIN outputs were calculated by multiplying the net transport of the outgoing, upper layer at the mouth of the inlet by the DIN concentrations within that layer. Sediment DIN outputs were determined in the same manner as the sediment inputs. Phytoplankton uptake was measured during primary productivity experiments, which occurred twice per month for nine months; these rates were then integrated over the water column

and multiplied by the area for the different portions of the inlet at MLLW (Newton et al., 1998).

Results

Sources of DIN

Figure 3 shows the average rate of DIN input from each source for the whole and inner inlet by month. The total amount of DIN entering the whole inlet ranged 3-fold between the wet winter months (November 1996–January 1997) and dry summer months (July–September 1997). Similarly, DIN inputs to the inner inlet varied by a factor of four between the wet and dry seasons. The ratio between the individual months of January and August was nearly five-fold.

The main source of nutrients to the whole inlet in all months was Puget Sound (Figure 3, top panel; Table 1). Likewise, it was the primary source for the inner inlet except in August 1997. The inner inlet received nearly all of the nutrients entering the inlet from freshwater sources, including wastewater treatment plants, rivers, and streams. Rainfall and sediments contributed more DIN directly to the central and outer portions of the inlet versus the inner inlet due to the larger surface area in those segments of the inlet.

Because the inner inlet received most of the incoming freshwater nutrients, the relative impacts of these DIN sources on the inner inlet were different than those on the whole inlet. For the inner inlet, Capitol Lake was the second largest source of DIN from November to May, while the sediments and LOTT varied as the third and fourth largest contributors during these months (Figure 4, bottom panel). From July through September, sediments were a larger source than Capitol Lake, with LOTT generally being the fourth largest supplier. The contribution of the sediments is more clearly seen with the large contribution by Puget Sound removed (Figure 4). Capitol Lake added slightly more DIN to Budd Inlet than the sediments during the month of June.

For the whole inlet, Capitol Lake was the second largest source of DIN from December through April with the sediments being the third largest contributor (Figure 4, top panel). For November, and for and May through September, these roles reversed, with sediments as the larger of the two sources. With the exception of the month of August, LOTT was the fourth largest supplier of DIN to the inlet.

LOTT is not a major contributor of DIN to Budd Inlet when compared to the other sources. Throughout this study, LOTT contributed less than 5% of all DIN entering the whole inlet from measured sources. While very small, additional unmeasured sources would further reduce LOTT's percentage. When only the inner inlet was considered, LOTT supplied less than 8% of the DIN. During winter months, LOTT's contribution to the inner inlet typically was 7% or less and during summer was lower than 4%, with the exception of 8% during August 1997. During that month, LOTT's total DIN discharged was the same as during June and September; however, both Capitol Lake and Puget Sound reached their minimum input levels, thereby increasing LOTT's percentage of the total contributions.

To summarize winter to summer differences for contributions from each type of source, the range of the contributions during winter (November–January) and summer (July–September) are shown in Table 1. The year is divided this way because LOTT operates its nitrogen removal facilities from April to October. For the remainder of the year the nitrogen removal facilities operate in a diminished capacity. Note that regardless of season and segment of inlet, LOTT is the fourth largest contributor in most months, ranging between 1% and 8%.

Table 1. Percentage of total DIN loadings to Budd Inlet by source and season

Source	**Whole Inlet**		**Inner Inlet**	
	Winter (Nov. 1996–Mar. 1997)	**Summer** (Apr.–Sept. 1997)	**Winter**	**Summer**
Puget Sound	78–83	60–84	73–78	47–82
Sediments	2–11	6–34	0.4–6	0.7–37
Capitol Lake	7–11	1–8	12–17	3–14
LOTT	2–5	1–3	3–7	2–8
Other inputs	1–2	1–3	1–2	1–5

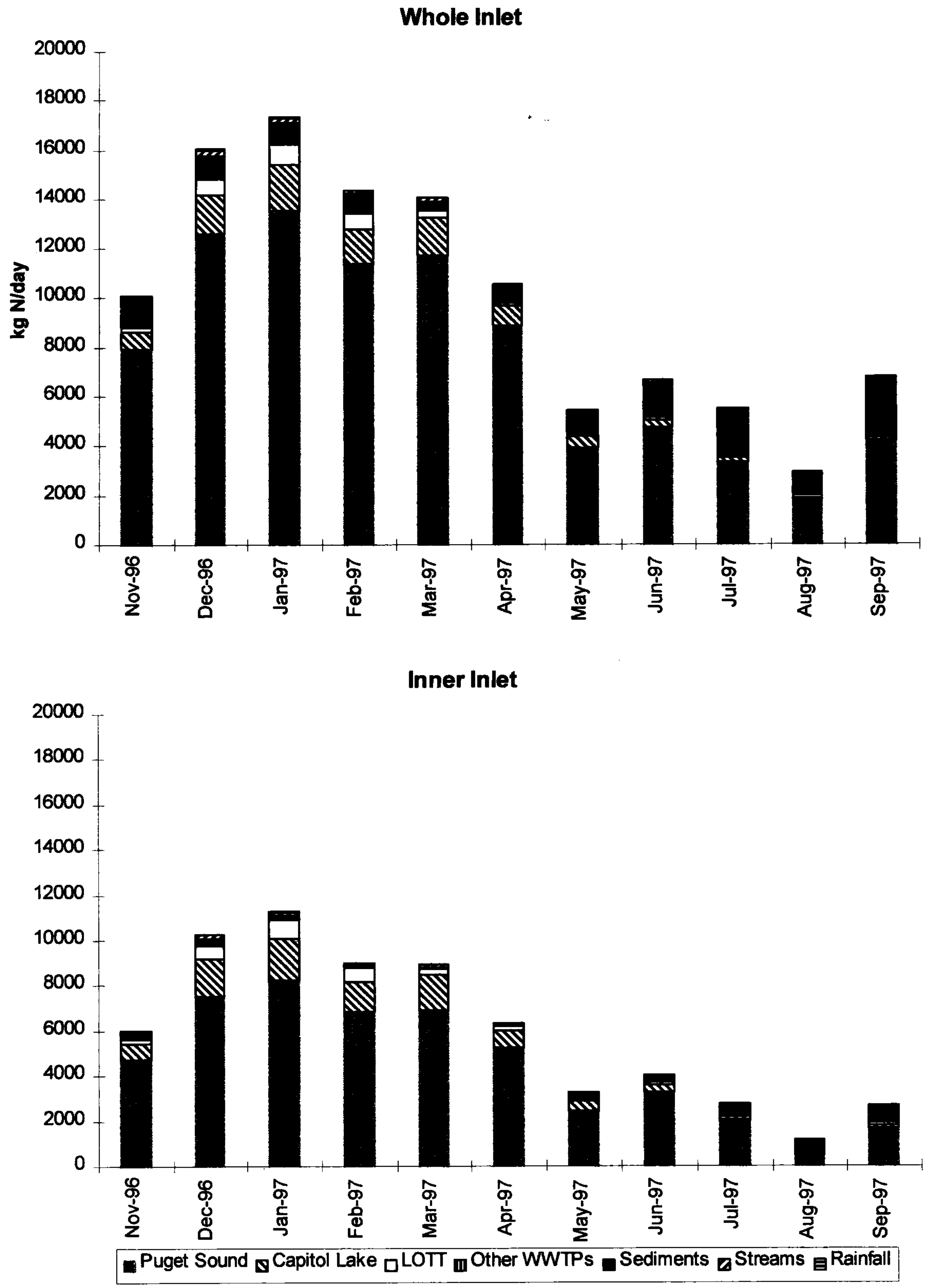
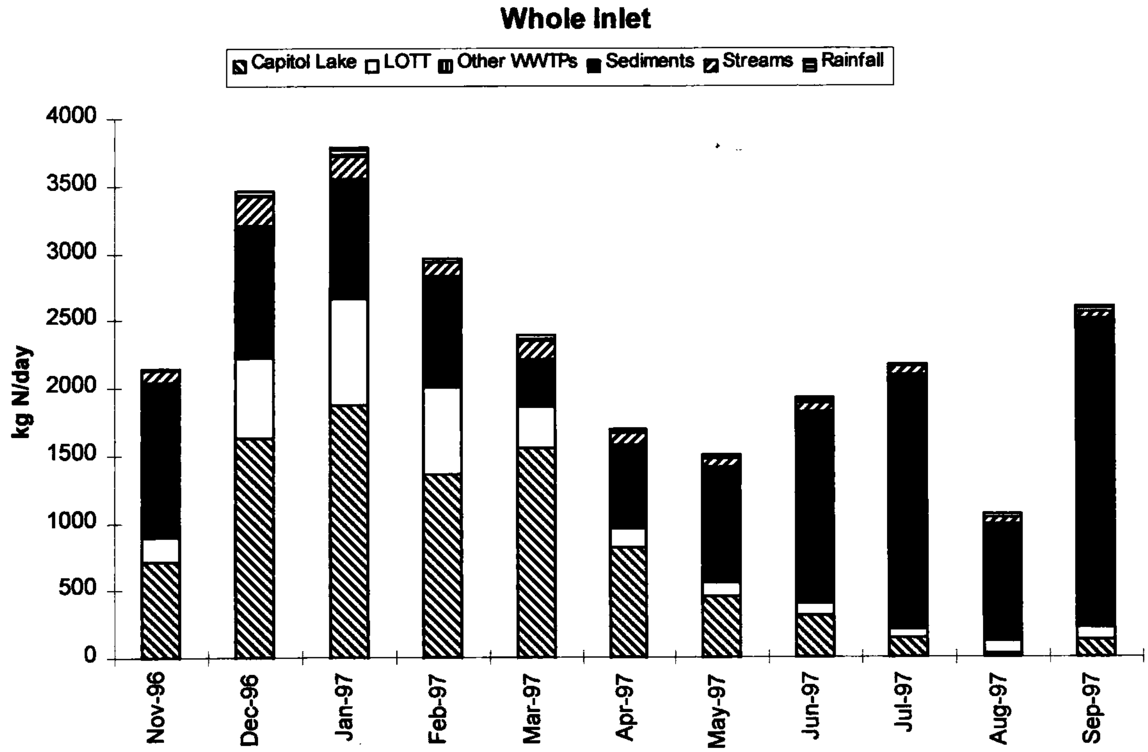


Figure 3. Dissolved inorganic nitrogen loading to Budd Inlet, November 1996–September 1997.



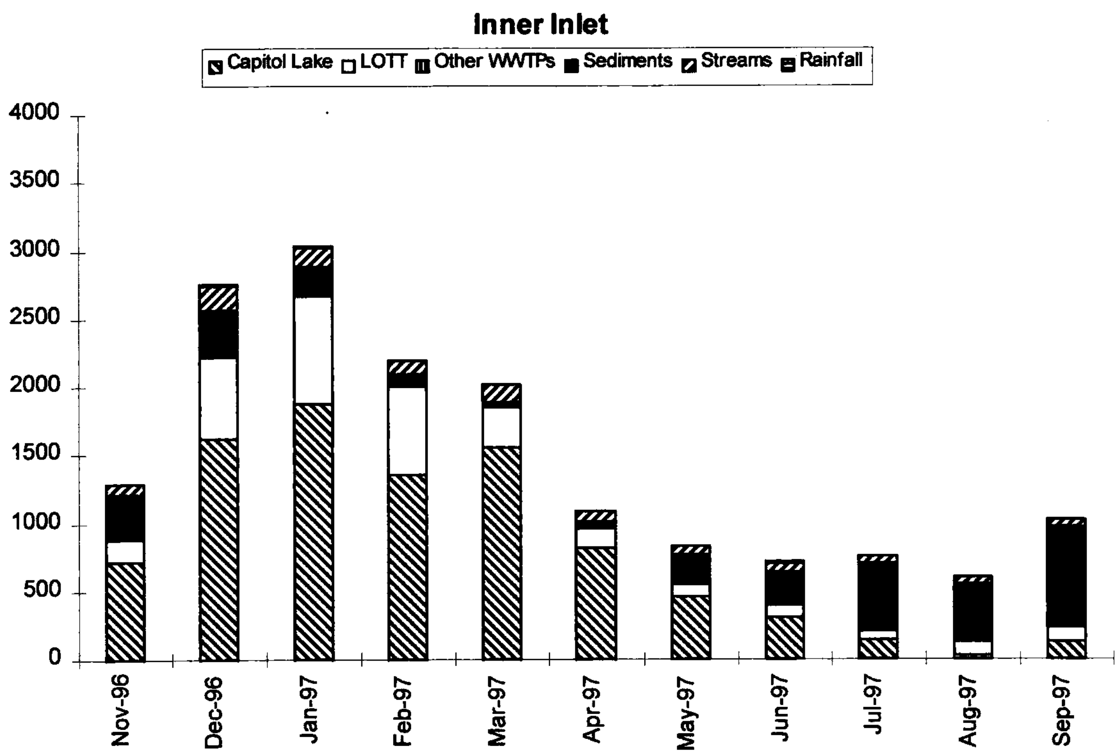


Figure 4. Dissolved inorganic nitrogen loading to Budd Inlet without Puget Sound contributions, November 1996–September 1997.

The sediments played a significant role in the DIN inputs, providing up to one third of the DIN entering the whole and inner inlets during some months. This input was a direct result of increased water temperatures and the loading of fresh organic materials to the sediments from dying plankton blooms. The importance of this organic loading to the sediments was conceptually understood in terms of its effect upon sediment oxygen demand, but not as well documented for its importance to nutrient recycling in Budd Inlet. These recycled nutrients represented only about 22% of the DIN reaching the sediments, with approximately 12% of this nitrogen converted into nitrogen gas and subsequently lost to the atmosphere (Budd Inlet Scientific Study Final Report, 1998).

Sinks of DIN

The sinks of DIN varied by season, mostly due to changes in primary productivity. Water exiting to Puget Sound was the primary DIN sink during the winter months; in contrast, phytoplankton nutrient uptake was the primary sink during the summer months (Figure 5). Upon receiving favorable light conditions in late March and early April, the phytoplankton population increased and began utilizing DIN at rates sufficient to lower concentrations within the water column. As a result, the concentration in outgoing Puget Sound water decreased. In addition, the net transport rate within the inlet began slowing after March as less fresh water entered the inlet during late spring and summer. The combination of these two decreases led to a smaller DIN load out of the inlet. Only a small amount of DIN was lost to the sediments throughout the year. In summary, nearly all DIN loss was due to transport out of the inlet during winter months, while the dominant loss in the summer was phytoplankton uptake.

Balance of Inputs and Losses

The balance of the DIN inputs and losses was computed (Figure 6). In this figure, the additional loss of DIN due to utilization by phytoplankton shows the dramatic influence phytoplankton have over the balance of the inputs and losses, and therefore the resulting concentrations within the marine waters. In general, periods of net inputs correspond to the seasonal periods that DIN concentrations within the marine waters were increasing or remained steady (September 1996–March 1997). Periods of net loss correspond in general to when DIN concentrations decreased or remained at low levels in the marine waters (April–August 1997). Phytoplankton uptake of DIN heavily influenced the balance of inputs and losses during primarily April–September 1997 as expected.

While this balance shows general agreement to increases and decreases of marine DIN concentrations, it is apparent that some future refinement may be necessary. In particular, inputs and losses during December–February should nearly balance, as marine concentrations remained steady during this period. The largest net loss was anticipated to have occurred during April–May when the largest decrease in marine DIN concentrations occurred, rather than August. A decrease in marine DIN concentrations did occur within August, but not to as large an extent as during April. These results suggest two things: 1) that during winter, DIN losses may be underestimated as that is the time of limited sediment flux and primary production data; and 2) that during spring and summer, decay of dead phytoplankton, and the subsequent release of nitrogen back to DIN must be occurring within the water column to a greater extent than anticipated, and therefore not just occurring at the sediments. A term to represent this process was incorporated into the water quality model. Another factor affecting spring and summer rates could be that the DIN input from the sediments and the spatial variability in phytoplankton uptake of nutrients was greater than our measurements allowed us to interpret.

Summary

LOTT does not appear to be a major influence on the DIN dynamics when analyzed in relation to the contributions of Puget Sound, the sediments, and Capitol Lake. LOTT's DIN contribution to Budd Inlet was very small, providing less than 8% of the total DIN entering the inlet. In contrast, Puget

Sound was the dominant source throughout the study and contributed between 60–84% of total DIN. The role of the sediments varied more seasonally than other sources, becoming a larger player during the summer months when the role of other potential inputs such as Capitol Lake decreased. Of the freshwater sources, Capitol Lake was the dominant input and had strong seasonal variation. Phytoplankton played an important part in the nutrient and DO dynamics of Budd Inlet by utilizing nutrients in the water column and subsequently returning a portion of these nutrients to the sediments.

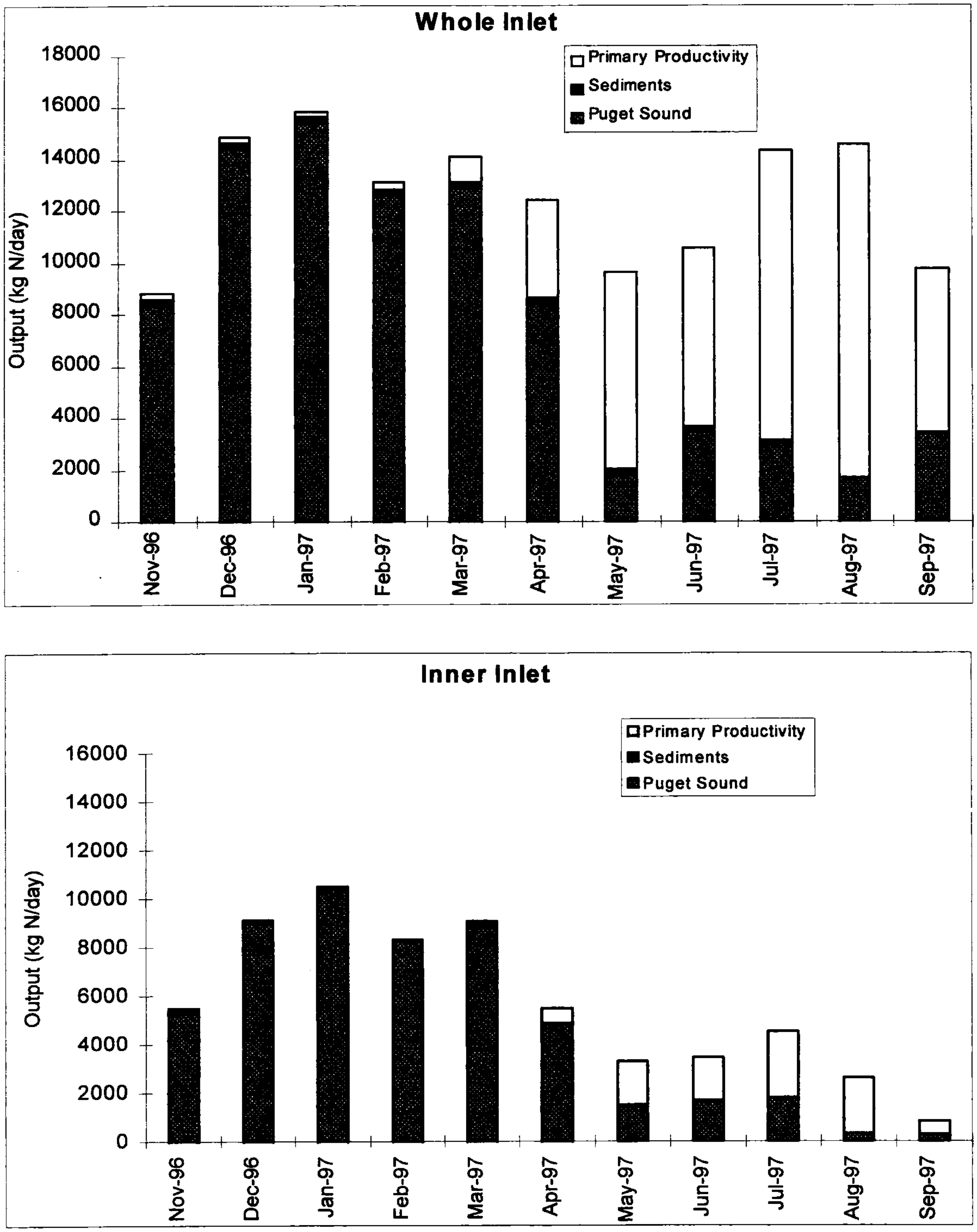


Figure 5. Sinks of dissolved inorganic nitrogen in Budd Inlet, November 1996–September 1997.

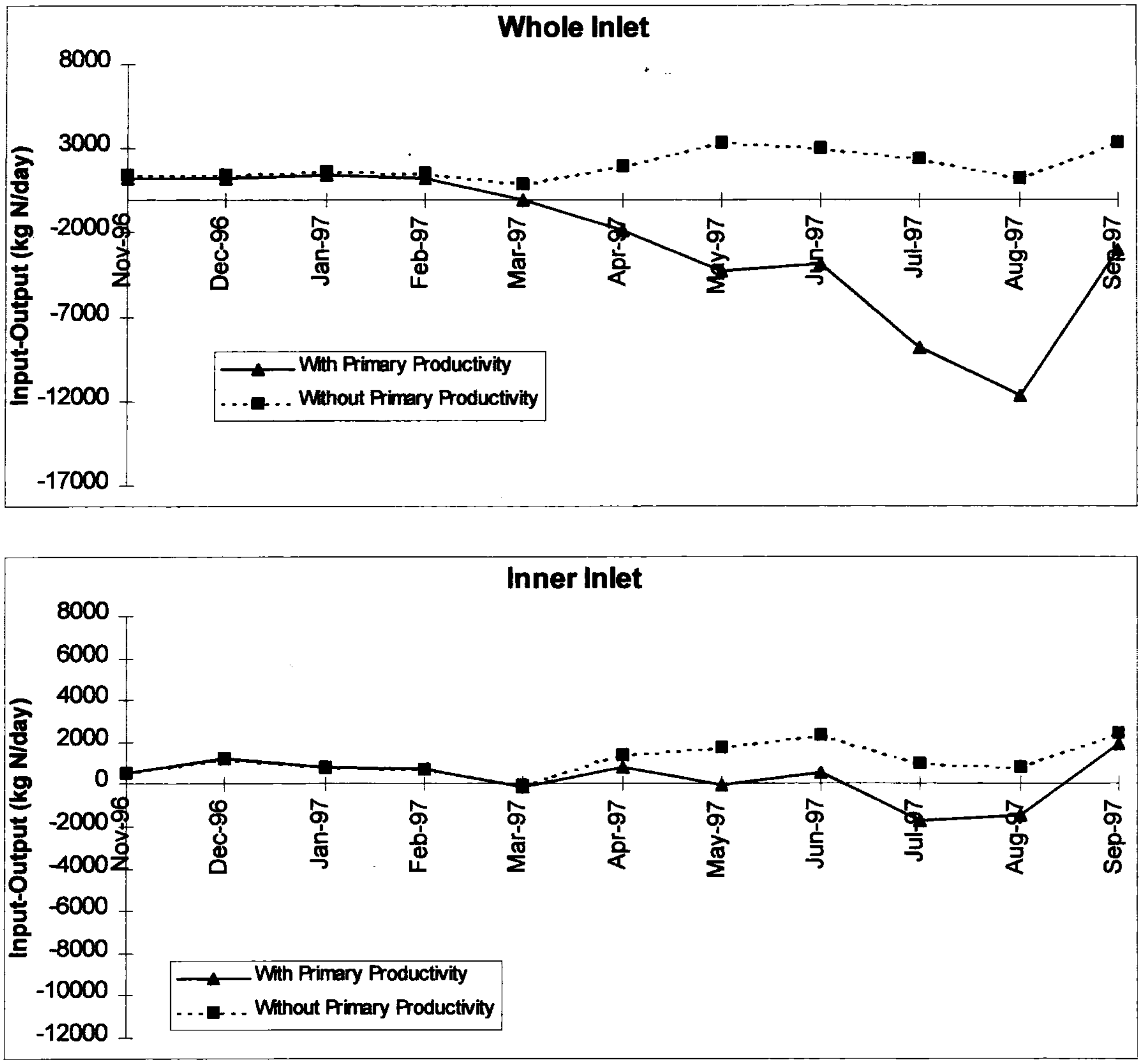


Figure 6. Balance of inputs and outputs in Budd Inlet, November 1996–September 1997.

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Primary Productivity in Budd Inlet During 1997: Seasonal Patterns of Variation and Controlling Factors

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Introduction

The factors controlling the magnitude of primary production in a particular water column are complex, hence to understand and difficult to discriminate. Because primary productivity represents the product of m and B, where m is the specific growth rate (d^{-1}) and B is the biomass of the phytoplankton population (mg m^{-3}), a high primary production can be driven by either or both terms. The complexity arises because these terms in turn depend on both growth factors, such as solar radiation, dissolved nutrients, water temperature, as well as loss factors, such as grazing by zooplankton, mixing, and sinking within the water column. Thus, low primary production could be driven by low growth rates or from high loss rates to the biomass, just as high production can be driven by high growth rates or by a very large but slowly growing population.

We did not measure immediately. In order to quantify the specific growth rate of phytoplankton, and thus, if growth seems limited or not, one can calculate the P:B ratio (production/biomass). Phytoplankton production is measured in carbon units whereas phytoplankton biomass is measured via chlorophyll *a*. Unfortunately, the bias introduced to the P:B ratio from the variation in the C:chl (carbon/chlorophyll) conversion ratio can be substantial. Chlorophyll *a*, while in all phytoplankton, can vary widely in terms of its cellular quota due to photoadaptation, nutrient availability and other factors. In temperate waters where light changes dramatically with season and with depth, photo-adaptation can cause the chlorophyll per cell to vary widely, easily by a factor of four or more (Newton and Morello, 1998). This variability in chlorophyll per cell can dramatically bias estimates of the specific growth rates from the P:B ratio. Therefore, the P:B ratios presented here may not be indicating differences in growth, but rather, differences in cellular chlorophyll content.

Methods

Primary production was determined from the uptake of ^{14}C sodium bicarbonate in water samples drawn from Budd Inlet. Experiments were conducted at four stations, representing the three Inlet segments: BI-5 in the Inner Inlet; Loon-1 and BA-2 in the Central Inlet; and BD-2 in the Outer Inlet (Figure 1). The four sampling stations were visited approximately every three weeks during 1997 (Table 1), from January through October. Only stations BI-5 and Loon-1 were occupied until April, after which all four stations were sampled.

At each station, water samples were collected in Niskin bottles from six different light levels, corresponding to 100%, 50%, 25%, 12.5%, 6.25%, and 1.6% of surface light. The depth of the euphotic zone and these light levels were determined with a Secchi disk using standard techniques (Parsons et al., 1984), deriving the light extinction coefficient (k, in m^{-1}) for Puget Sound waters (Newton et al., 1997) as:

$$k = 1.6/\text{Secchi disk depth.} \quad (2)$$

From each light level, chlorophyll *a*, nutrients, and primary productivity (replicate light bottles and one dark bottle) were sampled. Replicate profiles of productivity bottles were filled, one for the ambient treatment and one for the nutrient spike treatment. For the nutrient spike, we added an initial concentration of 10 mM nitrogen (NH_4Cl) and 1 µM phosphorus (KH_2PO_4) to the seawater. To monitor nutrients over the course of the experiment, extra surface bottles were filled and sampled at 0 hr and 24 hr for nitrate, nitrite, ammonium, orthophosphate, and silicate.

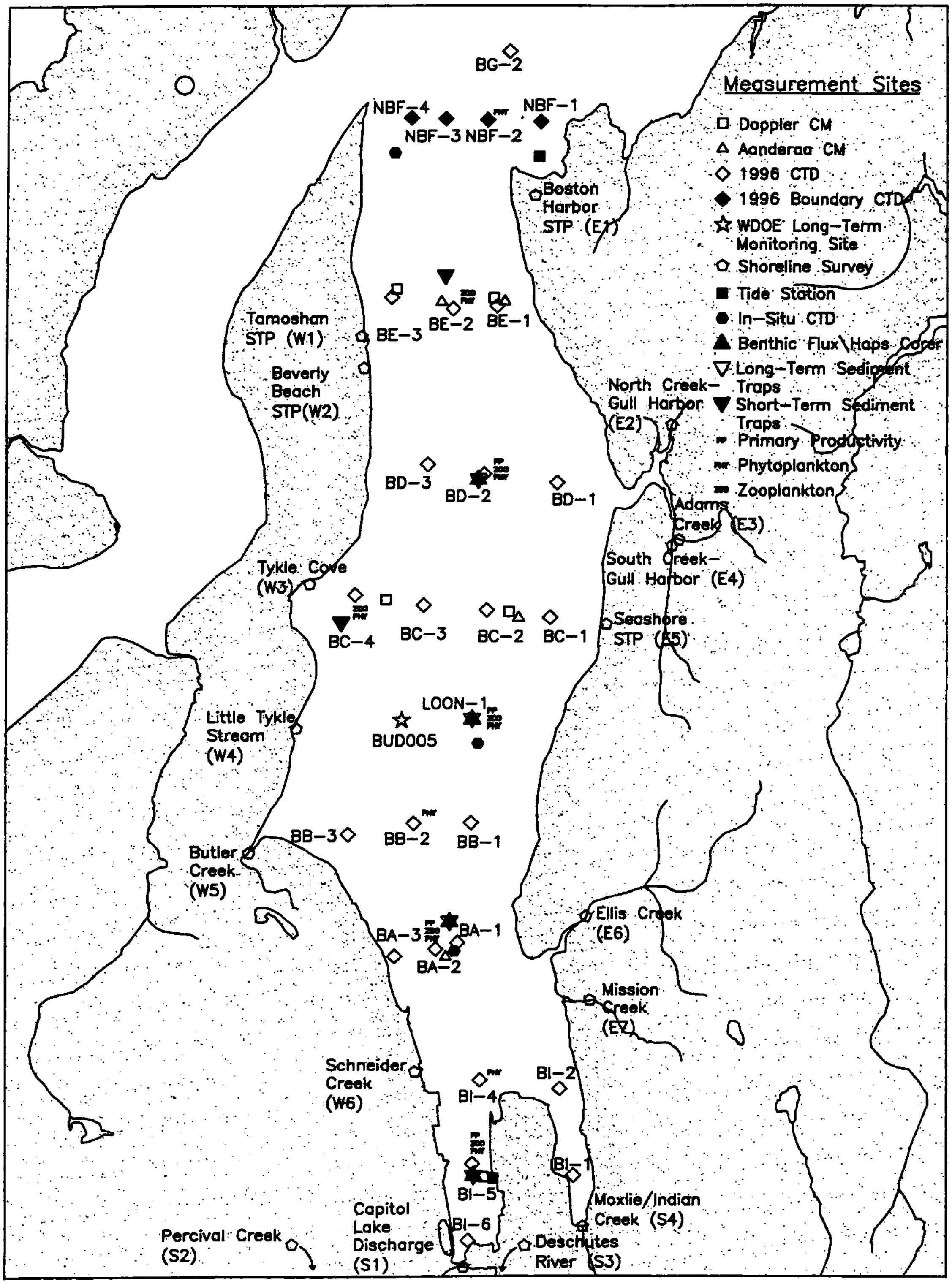

Figure 1. Map of stations and segments in Budd Inlet.

Table 1. Dates and station locations for primary production experiments in Budd Inlet.

		Stations			
		BI-5	**BA-2**	**Loon-1**	**BD-2**
		47 03.09 N	47 04.32 N	47 05.52 N	47 06.87 N
Experiment #	**Date**	122 54.27 W	122 54.65 W	122 54.53 W	122 54.72 W
1	16-Jan-97	X		X	
2	23-Jan-97	X		X	
3	27-Feb-97	X		X	
4	20-Mar-97	X		X	
5	3-Apr-97	X	X	X	X
6	22-Apr-97	X		X	
7	5-May-97	X	X	X	X
8	19-May-97	X	X	X	X
9	12-Jun-97	X	X	X	X
10	30-Jun-97	X	X	X	X
11	14-Jul-97	X	X	X	X
12	4-Aug-97	X	X	X	X
13	18-Aug-97	X	X	X	X
14	11-Sep-97	X	X	X	X
15	25-Sep-97	X	X	X	X

We incubated the primary productivity samples for 24 hr under simulated *in-situ* conditions using an outdoor tank plumbed with running seawater at West Bay Marina, Budd Inlet. Prior to the incubation, each primary productivity bottle was inoculated with ^{14}C-labeled sodium bicarbonate and, if appropriate the nutrient spike, and then placed in screen bags to simulate the light level from which it was collected. After 24 hr, the bottles were filtered onto glass fiber filters (Whatman, GF/F, normal pore size 0.7m) and the filters placed in vials with EcoLume scintillation cocktail. The specific activity of the filtered particulates was measured in a Beckman scintillation counter. Primary production was calculated as mg C m^{-3} d^{-1} using the basic equations found in Parsons et al. (1984), subtracting dark bottle DPMs from light bottle DPMs. Chlorophyll and nutrient samples were analyzed as previously described (Cox et al., this volume).

Results and Discussion

We present the patterns observed in the data collected during January–September of 1997 at 2-3 week intervals. Interpretations of these data must be made with strong caution due to two important caveats: 1) phytoplankton populations are highly variable on time scales much shorter than two weeks (i.e., days), thus we may have missed much of the variation; and 2) interannual variation has been observed to be quite strong in Budd Inlet, thus the representativeness of 1997 data is not known. During Department of Ecology's bi-weekly monitoring study in 1992–1994, the maximal integrated chlorophyll concentrations found at inner Budd Inlet monitoring stations during the years 1992, 1993, and 1994 were 155, 70, and 220 mg m^{-2}, respectively, and these maxima were observed in September, June, and July, respectively (Eisner and Newton, 1997).

Seasonal Variation

A distinct seasonal pattern was evident in the ambient primary production that is consistent with a temperate location (Figure 2). There was lower production in winter with higher production occurring from May through the end of September. Often at temperate latitudes a pattern of spring and fall blooms with reduced production in summer is observed. However, in Budd Inlet primary production remained high throughout the summer. Phytoplankton biomass, as indicated by chlorophyll *a*, also showed a seasonal pattern but it was somewhat different than that of primary production. There were distinct maxima in early May and the period of mid-July through early September, with reduced abundance in late May through early July (Figure 2). However, since phytoplankton populations can change very rapidly (within a day or two), we could be missing much in terms of the seasonal dynamics.

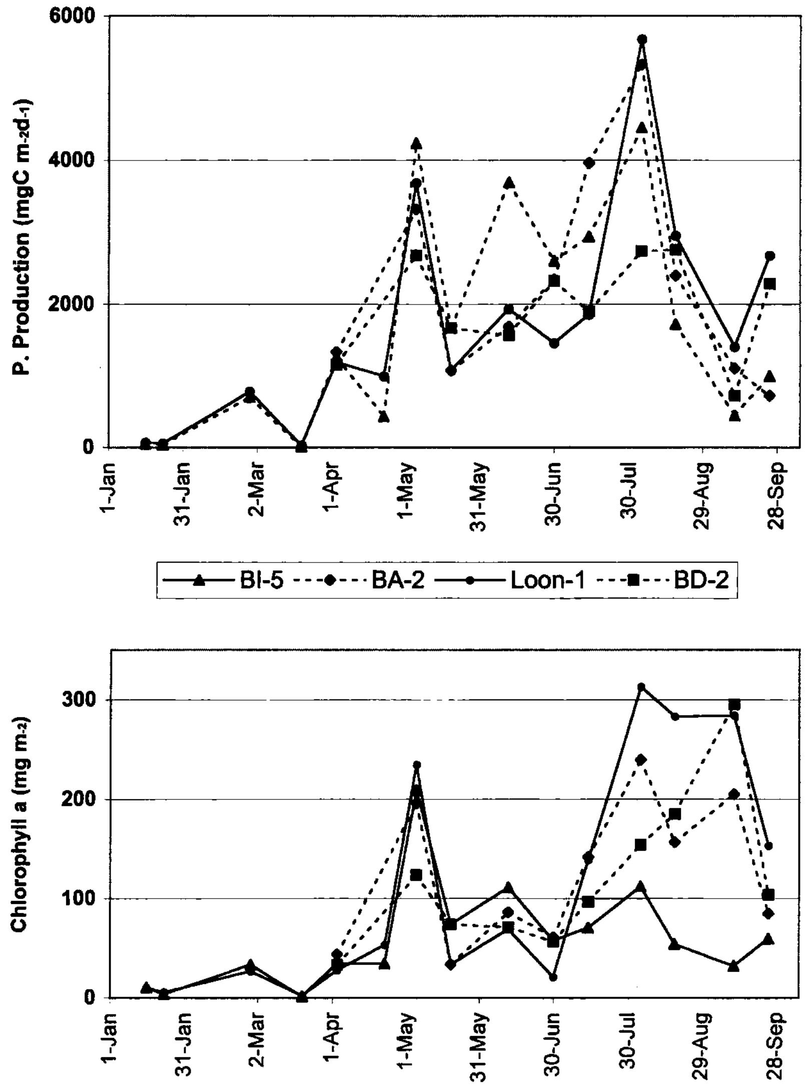

Figure 2. Seasonal pattern of primary production and phytoplankton biomass, as indicated by chlorophyll a. Values are integrated over the euphotic zone.

The P:B ratios calculated in Table 2 show highest values during April through August. This reflects an expected increase in growth rate during the temperate growing season. Photoadaptation to high light in summer can bias P:B ratios to be too high, just as low light adaptation can result in low P:B ratios.

Table 2. Primary productivity and water column conditions in Budd Inlet during 1997. Integrated variables are integrated over the euphotic zone.

Expt #	Date	Station	Integrated PP (mg C m^{-2} d^{-1})	Integrated chl (mg chl m^{-2})	P:B (mg C mg chl^{-1} d^{-1})	Euphotic zone (m)	Incident radiation (moles m^{-2} d^{-1})	Integrated DIN (mM m^{-1})
1	16-Jan-97	BI-5	46	10	5	11.2	2.39	383
		Loon-1	67	10	7	13.0	2.39	275
2	23-Jan-97	BI-5	32	3.4	9	5.5	12.8	162
		Loon-1	57	5.4	11	8.1	12.8	245
3	27-Feb-97	BI-5	700	33	21	13.0	21.7	408
		Loon-1	779	26	30	14.4	21.7	335
4	20-Mar-97	BI-5	6	1.1	5	1.7	32.6	31
		Loon-1	29	2.0	15	2.3	32.6	47
5	3-Apr-97	BI-5	1255	35	36	12.1	40.7	302
		BA-2	1331	43	31	17.0	40.7	321
		Loon-1	1185	27	43	18.7	40.7	347
		BD-2	1155	33	35	17.0	40.7	242
6	22-Apr-97	BI-5	428	34	13	3.5	17.8	50
		Loon-1	996	53	19	4.3	17.8	43
7	5-May-97	BI-5	4235	209	20	5.8	18.4	15
		BA-2	3319	196	17	5.2	18.4	23
		Loon-1	3687	235	16	5.8	18.4	53
		BD-2	2678	124	22	5.0	18.4	55
8	19-May-97	BI-5	1662	74	22	12.2	36.7	1
		BA-2	1291	27	48	12.2	36.7	2
		Loon-1	1075	33	32	7.2	36.7	40
		BD-2	1345	39	34	8.6	36.7	0
9	12-Jun-97	BI-5	3692	111	33	4.6	34.9	0
		BA-2	1685	86	20	4.3	34.9	5
		Loon-1	1931	69	28	4.0	34.9	54
		BD-2	1565	71	22	3.6	34.9	6

Table 2 (continued). Primary productivity and water column conditions in Budd Inlet during 1997. Integrated variables are integrated over the euphotic zone.

Expt #	Date	Station	Integrated PP (mg C m^{-2} d^{-1})	Integrated chl (mg chl m^{-2})	P:B (mg C mg chl^{-1} d^{-1})	Euphotic zone (m)	Incident radiation (moles m^{-2} d^{-1})	Integrated DIN (mM m^{-1})
10	30-Jun-97	BI-5	2601	58	45	12.2	41.3	108
		BA-2	2342	61	38	11.5	41.3	177
		Loon-1	1459	21	70	16.5	41.3	161
		BD-2	2322	57	41	19.4	41.3	67
11	14-Jul-97	BI-5	2639	71	37	6.5	40.3	2
		BA-2	3963	142	28	5.0	40.3	10
		Loon-1	1856	139	13	5.0	40.3	76
		BD-2	1896	97	20	5.0	40.3	3
12	4-Aug-97	BI-5	4448	112	40	7.2	51.4	8
		BA-2	5325	240	22	8.6	51.4	17
		Loon-1	5679	314	18	8.6	51.4	17
		BD-2	2736	154	18	9.4	51.4	4
13	18-Aug-97	BI-5	1719	54	32	7.2	27.0	3
		BA-2	2394	156	15	7.2	27.0	66
		Loon-1	2951	283	10	10.1	27.0	33
		BD-2	2758	185	15	14.4	27.0	6
14	11-Sep-97	BI-5	446	32	14	15.8	21.1	6
		BA-2	1098	205	5	4.3	21.1	4
		Loon-1	1406	284	5	3.6	21.1	170
		BD-2	716	295	2	5.0	21.1	4
15	25-Sep-97	BI-5	996	60	17	7.9	18.4	61
		BA-2	715	85	8	5.8	18.4	124
		Loon-1	2676	153	17	8.6	18.4	161
		BD-2	2282	104	22	10.8	18.4	55

Budd Inlet is a highly productive location, even within Puget Sound. Despite its shallow depth, the integrated production approached 6000 mg C m^{-3} d^{-1} (Figure 2). Another regional bay that has been well studied is Dabob Bay, a northward offshoot of Hood Canal (Downs and Lorenzen, 1985 and references within). The maximum primary production observed in an annual cycle during the years 1982–1985 ranged ~2000 to 4500 mg C m^{-3} d^{-1} (Downs, 1989). The water column at the sampling site in Dabob is 110 m deep whereas Budd Inlet stations average only 10 m. Often the euphotic zone extended beyond the sea–bed in Budd Inlet (Figure 3) meaning that sufficient light for photsynthesis was available to the entire water column. Phytoplankton biomass, as indicated by chlorophyll *a* integrated over the euphotic zone, was also comparatively high in Budd Inlet, with a seasonal maximum at just over 300 mg chl m^{-2} (Figure 2). Similar values for Dabob Bay for 1982–1985 ranged ~125 to 225 mg chl m^{-2}. The 1997 data are higher than that found in the Inner Inlet by Ecology during the 1992–1994 monitoring as previously mentioned in this section; however, values for the central Inlet (where the greatest population occurs) are not available, due to differences in sampling technique.

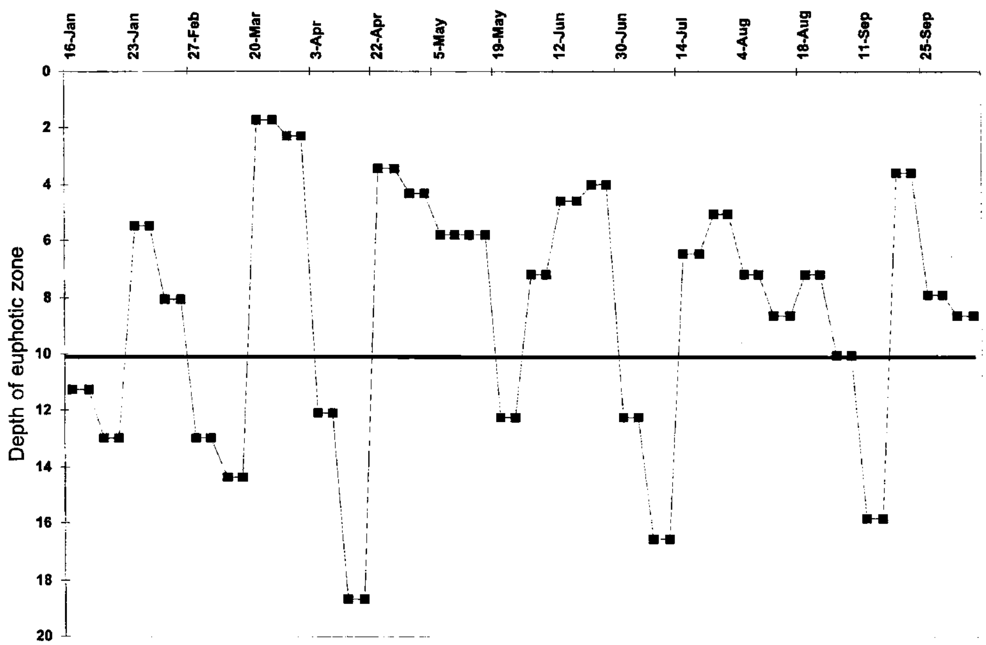

Figure 3. Depth of the euphotic zone (1% of surface radiation) at BI-5 and Loon-1 over the course of study. Seabed depth at these stations is 10 m.

Nutrients collected from the same bottles as the productivity samples showed a marked decline during the month of April (Figure 4) that inversely mirrored the increase in primary production. Based on these results, we conclude that for 1997, the spring bloom appeared to occur in April. However, strong variation in the timing of the spring bloom occurs regionally due to forcing by weather-related attributes. The timing of the spring bloom is driven by weather, both solar radiation and wind stress, as well as by hydrographic conditions and river input. For Dabob Bay during 1982–1985, the onset of the spring bloom ranged February through May. As stated, caution should be used when interpreting seasonal patterns based on the 1997 data alone. Monitoring of Budd Inlet by Ecology in 1992–1994 did not occur commence early enough in the year to make this assessment.

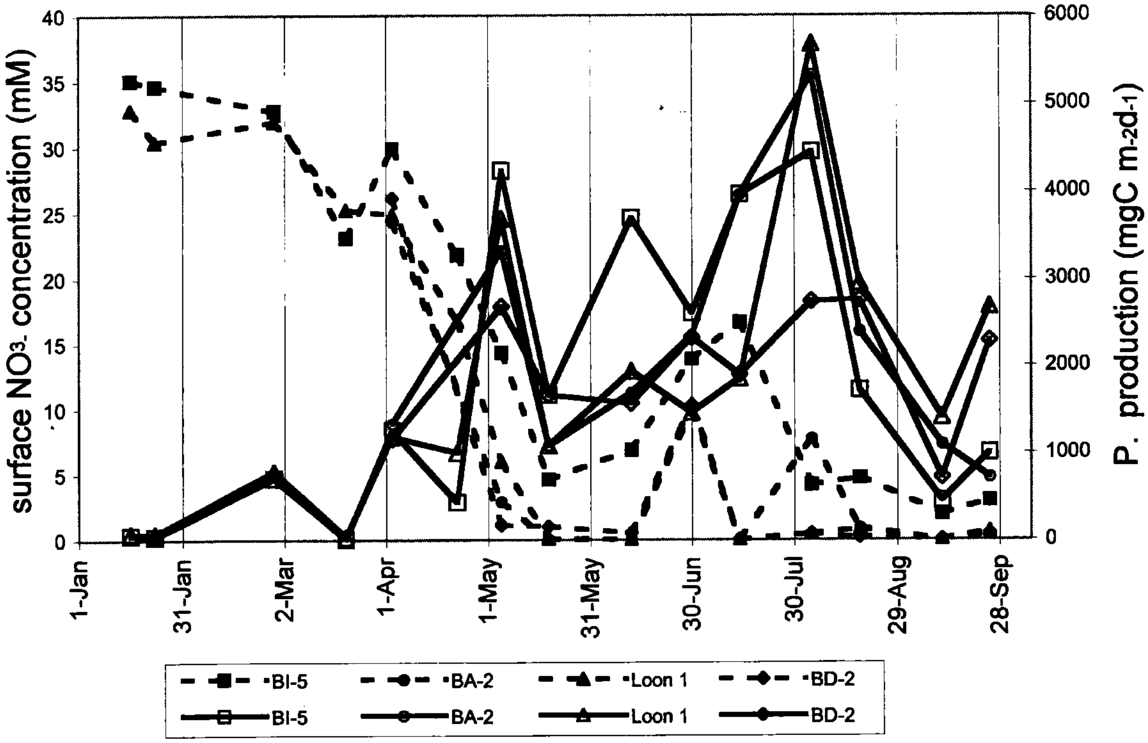

Figure 4. Seasonal plot of surface nitrate concentration (dotted lines) and primary production (solid lines) during 1997. Note that for all stations a marked decrease in nitrate in April May is accompanied by an upswing in production; however, note caveat regarding interannual variation in text.

Spatial Variation

There was no strong or consistent pattern in spatial variation of production or biomass in Budd Inlet, however the central bay stations (BA-2 and Loon-1) often had the highest values for both (Table 2). A similar observation of the highest phytoplankton abundance being found in the central inlet was seen in Ecology's previous assessment of Budd Inlet chlorophyll (Eisner and Newton, 1997). It is possible that either a weak gyre in the observed circulation or tidal pumping concentrates phytoplankton in this area (Ebbesmeyer, this volume).

Comparing BI-5 and Loon-1, since we have full time records for these stations, we see that integrated primary production was higher at BI-5 than Loon-1 in early summer (June–July), whereas in late summer (August–Sept.) both integrated production and especially chlorophyll were much lower at BI-5 than at Loon-1 (Figure 5). Looking at the other stations (Figure 2), we see that BI-5 had much lower chlorophyll than all stations during late summer. The mechanism for this pattern is not entirely clear. Despite the lower biomass in late summer, BI-5 production remained relatively high.

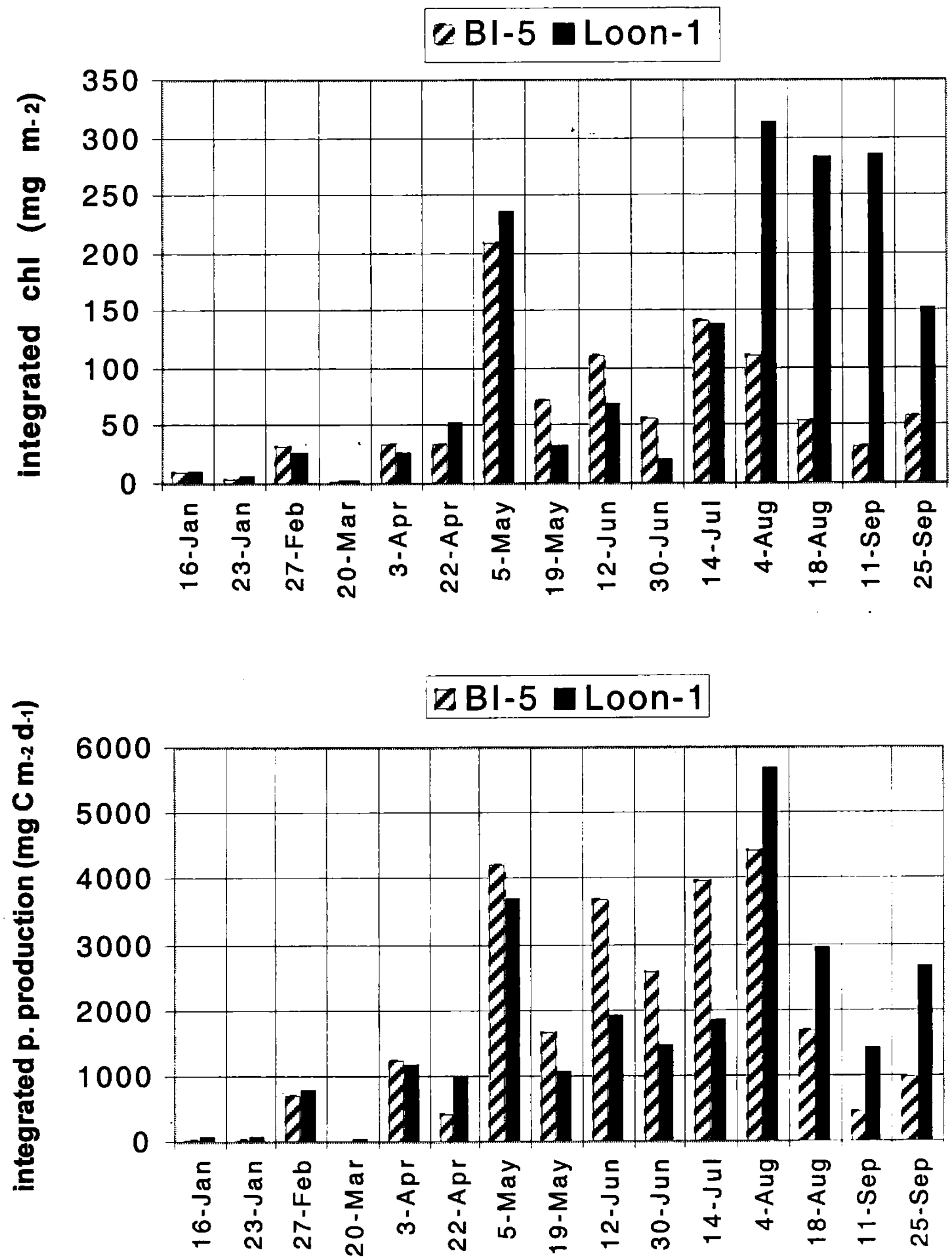

Figure 5. Seasonal values of integrated chlorophyll and primary production at BI-5 and Loon-1.

Nutrient data from at the productivity depths showed that the Inner Inlet (BI-5) had the highest surface nitrate and ammonium concentrations (Figures 6–7). Exceptionally high ammonium concentrations were found throughout the water column at BI-5, especially at depth where concentrations from May through July were 6–20 times higher than at any other station. The role of nitrogenous nutrient release from the sediments in the annual cycle and implications for flushing at this Inner Inlet station must both be regarded seriously in light of this strong signal.

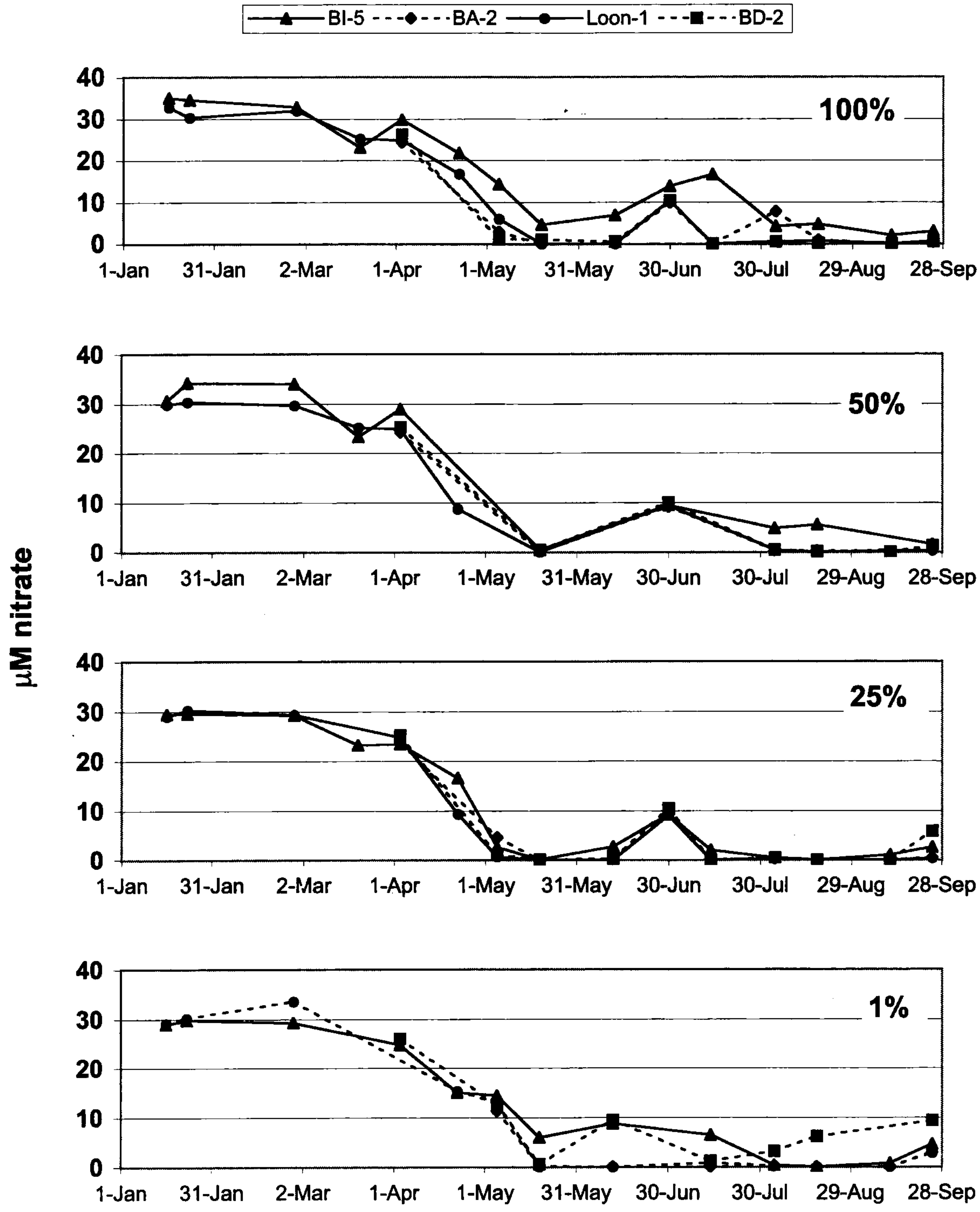

Figure 6. Ambient concentrations of nitrate (mM) at the depths of the various light levels as indicated.

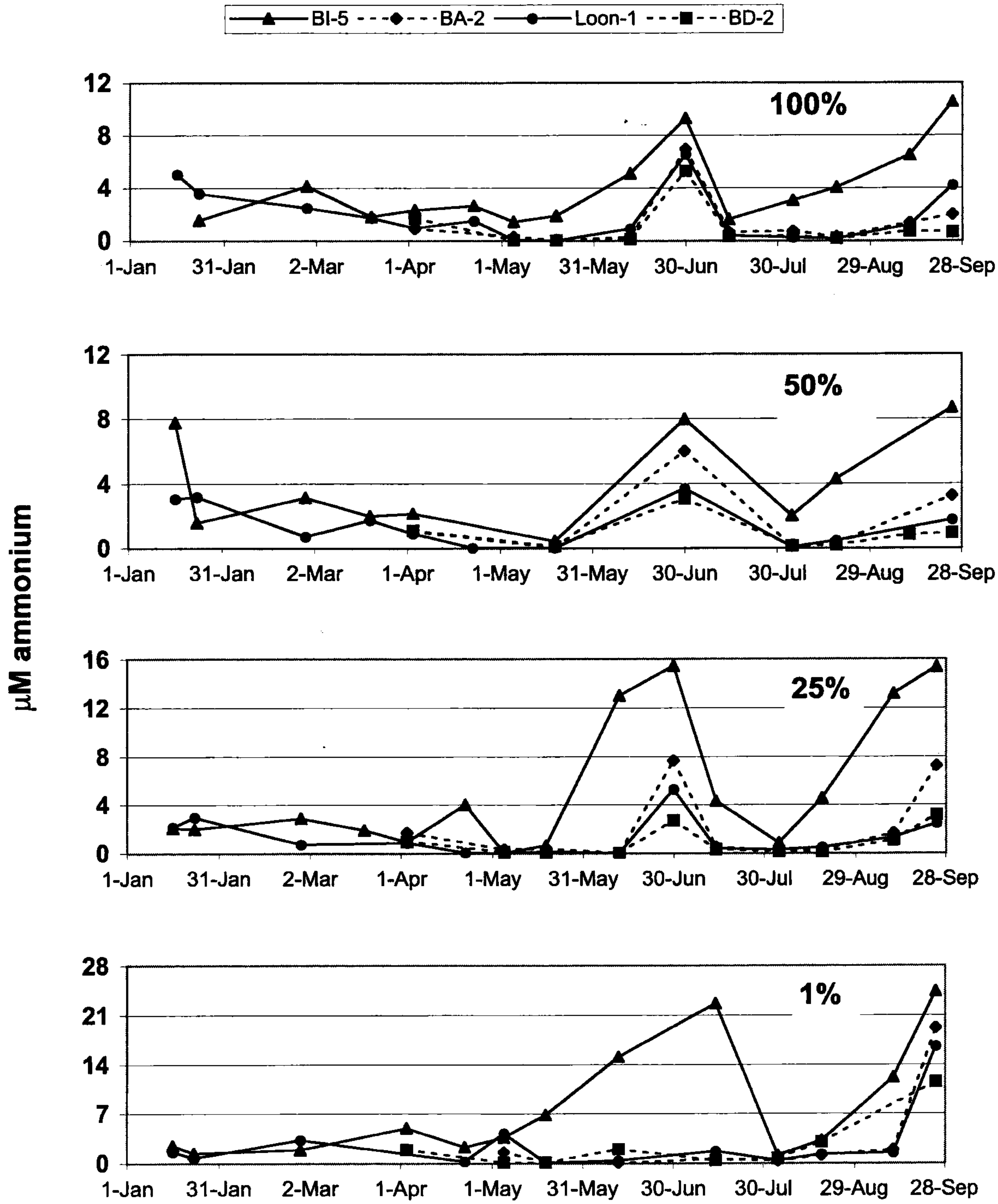

Figure 7. Ambient concentrations of ammonium (mM) at the depths of the various light levels as indicated.

Controls on Ambient Production

A shift from low production to higher production occurred in April 1997. The lower production period encompasses the first five experiments. Based on the nutrient and production data, all the remaining experiments have a similar character (Figure 4); however the chlorophyll data show the last four experiments to have distinctly high values (Figure 2). We thus compartmentalized the data into

these three bins (experiments 1–5, 6–11, and 12–15) to look for patterns in the correlation of production with possible controlling growth factors such as light, nutrients and biomass. Other factors, such as temperature and water column stability undoubtedly influence growth.

Phytoplankton biomass is one of the determinants of primary production (equation 1) so we would expect fairly strong correlations to be evident. For the first five experiments (Jan–Apr), we see a strong correlation (Figure 8a) that decreases but is still significant for all the experiments (Figure 9a). The most variation comes from the later experiments (Aug–Sept) and some of this may be due to variation in C:chl ratios.

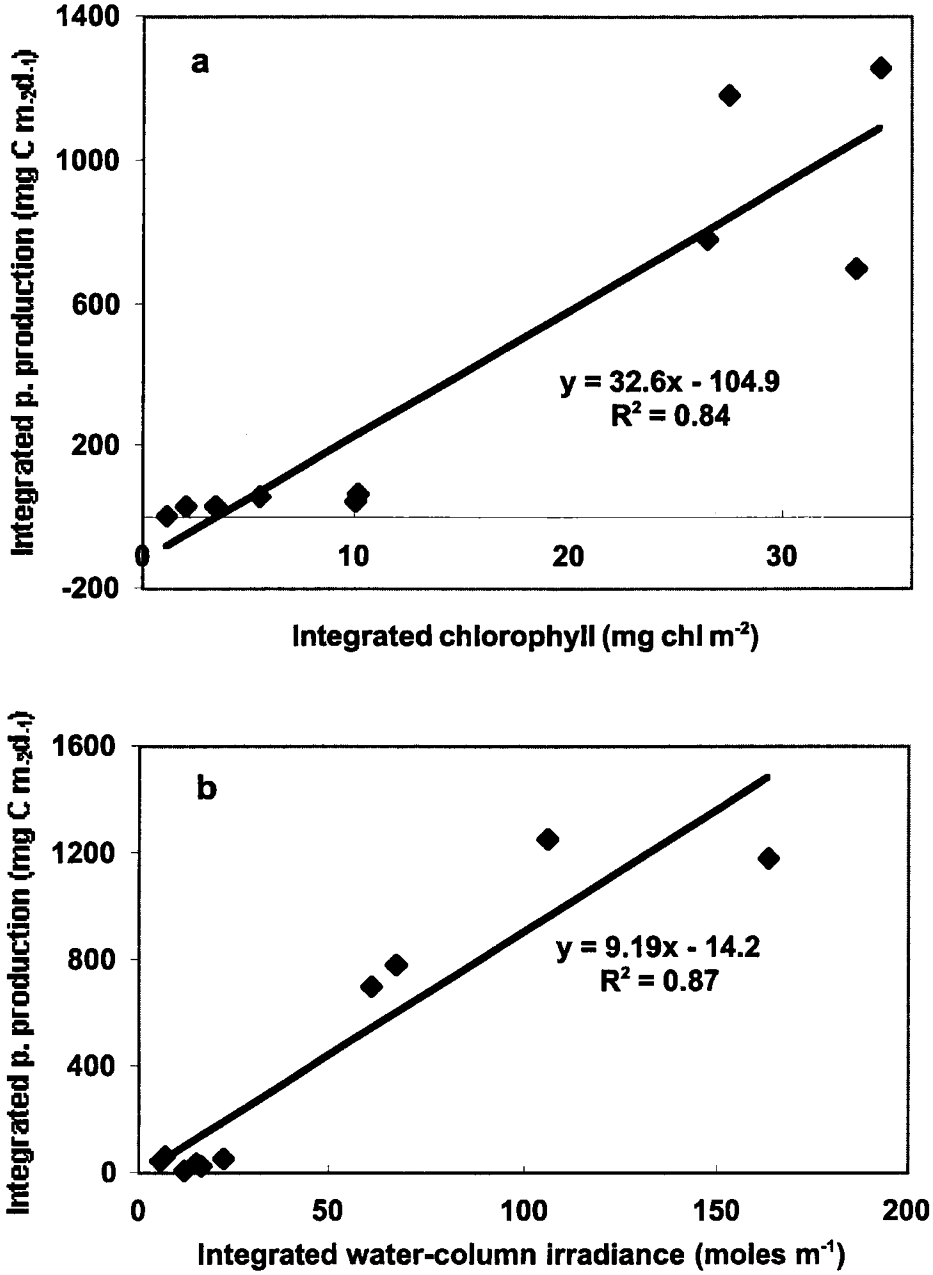

Figure 8. Correlation of integrated primary production with chlorophyll (A) and water column irradiance (B) for first five experiments (Jan-Apr, 1997) at BI-5 and Loon-1.

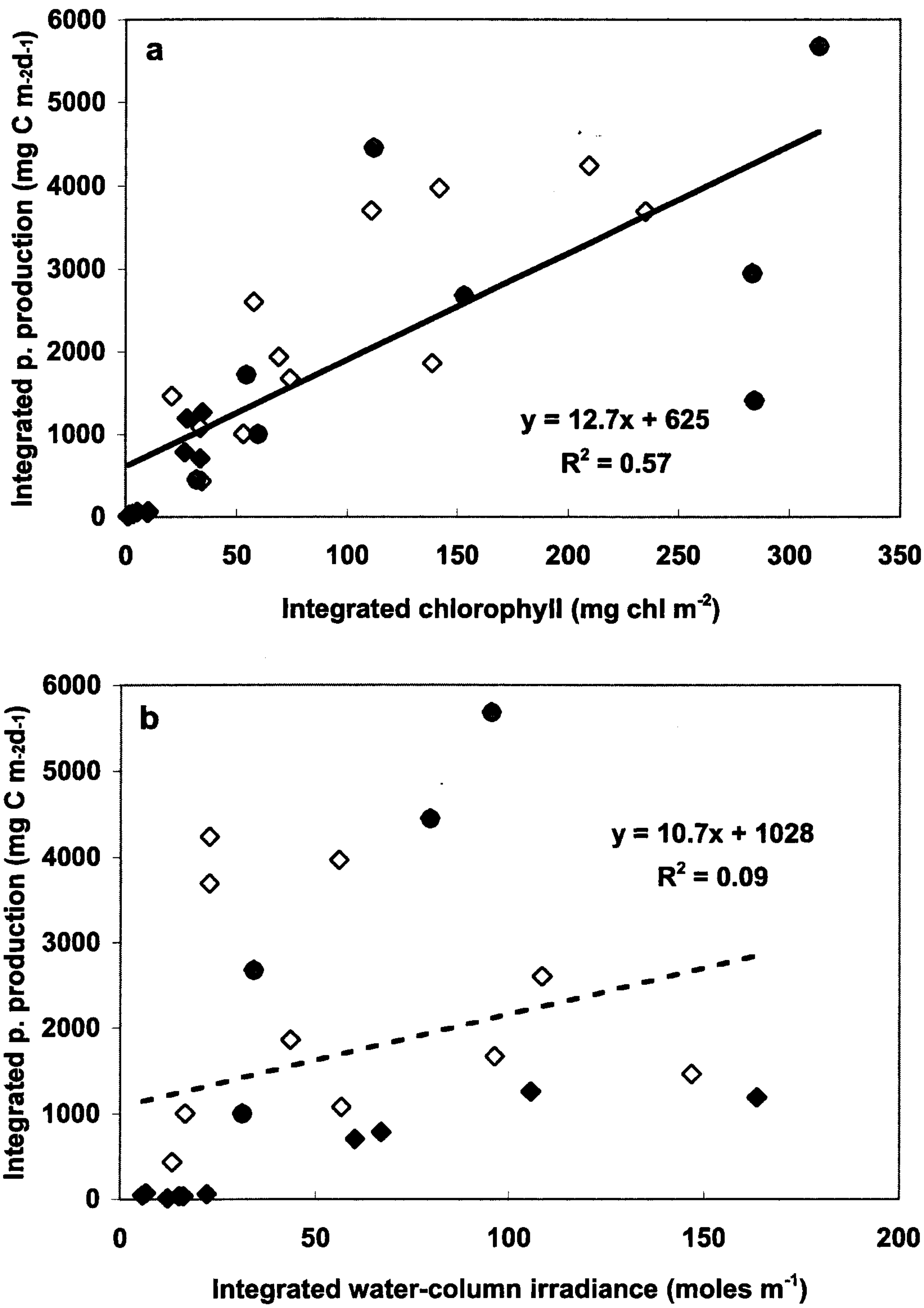

Figure 9. Correlation of integrated primary production with chlorophyll (A) and water column irradiance (B) for all 1997 experiments at BI-5 and Loon-1. Dark diamonds = 1¯5; open diamonds = expts 6¯11; grey diamonds = expts 12¯15.

Light available to phytoplankton is a function of the level of incoming solar radiation as well as how much particulate material there is in the water column that will attenuate the light. The particulate material may be either sediment or biogenic (e.g., phytoplankton cells). To account for this in our evaluation of light control on primary production, we calculated the light integrated within the euphotic zone. Primary production was strongly correlated with euphotic zone light during the early experiments (Figure 8b). As the year progressed, this relation weakened to a non-significant level (Figure 9b), indicating that other factors were exerting primary control on production.

Nitrogenous nutrients were in short supply (Table 2, Figures 6 and 7) during much of the growth season. It is difficult to interpret nitrogen control of growth based on ambient nutrient concentrations since concentrations cannot reflect uptake rates but, rather, the net balance of supply and uptake. To assess nutrient control of phytoplankton growth we added nutrient spikes; these results are discussed below and show that nutrients play a vital role in controlling growth, especially from May through September.

Effect of Nutrient Addition

If light appears to exert the primary control production during the Jan–April time period, then what effect would nutrients have on ambient production at that time? This was assessed using the nutrient spike results.

As shown in Figure 10, the addition of nutrients had a strong positive effect on production for the experiments from May through August. However, since ambient production is so much lower before May, an expanded scale is necessary to view the wintertime results. As shown in Figure 11, there were two instances of increased production during the Jan–April time period. Taken as a percentage, ambient production increased by 10–39% in this time period (Figure 12). This increase pales in comparison with the up to 80% increases noted in June–July. However, at issue is the quantity of carbon produced from N-fertilization and what this could mean to the oxygen debt in the bottom waters of Budd Inlet.

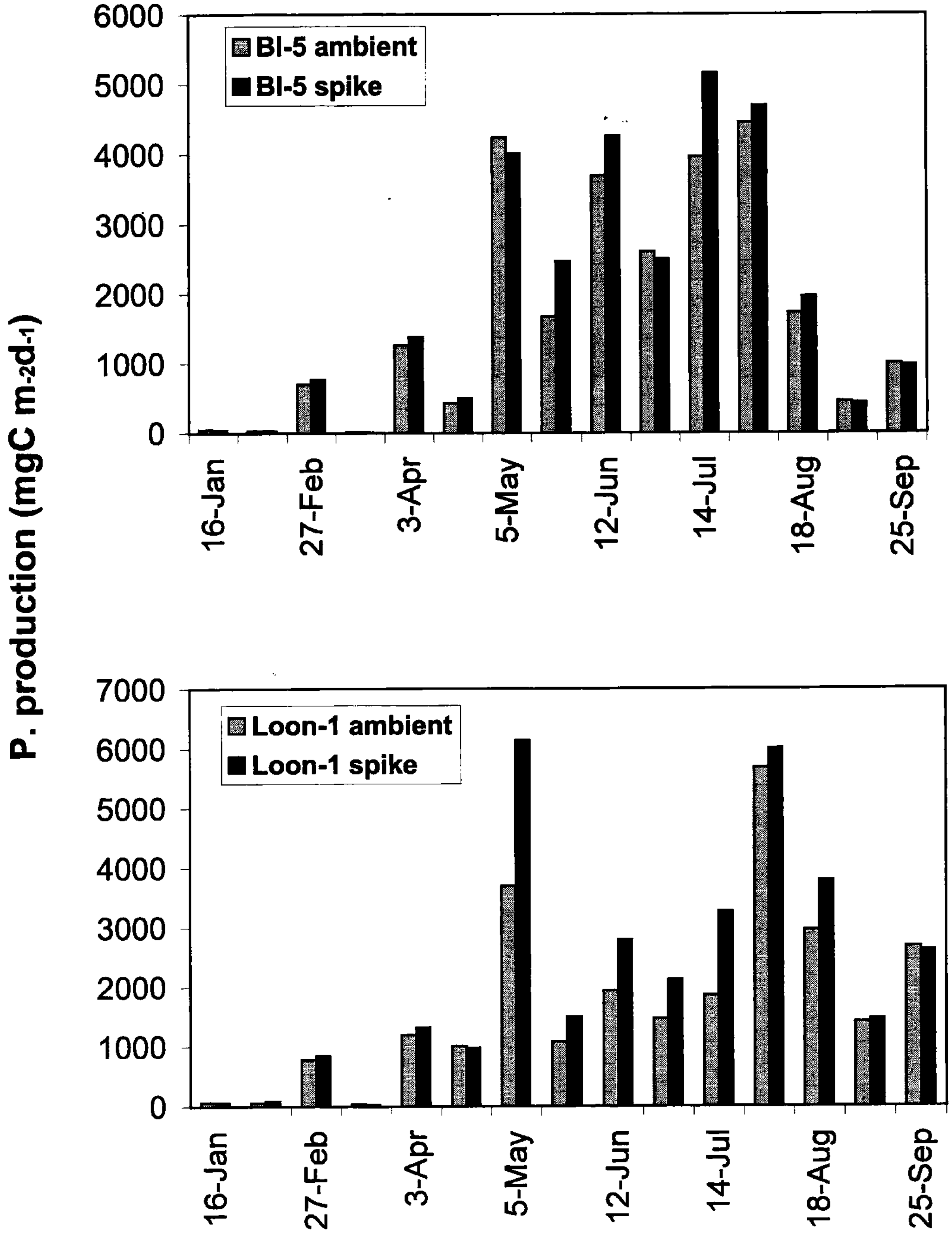

Figure 10. Effect of added nutrient spike on ambient primary production in Budd Inlet.

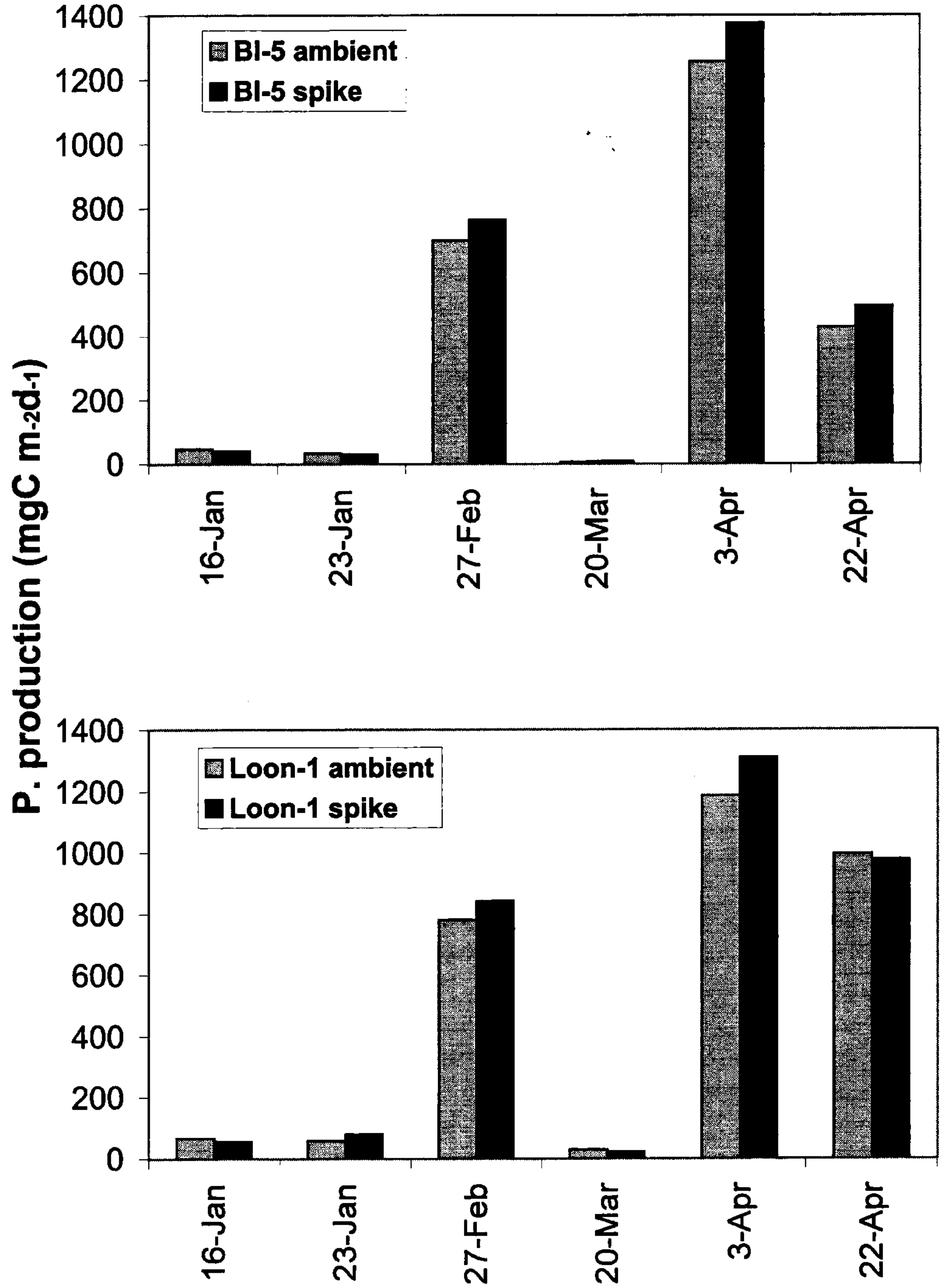

Figure 11. Effect of added nutrient spike on ambient primary production in Budd Inlet in winter and early spring.

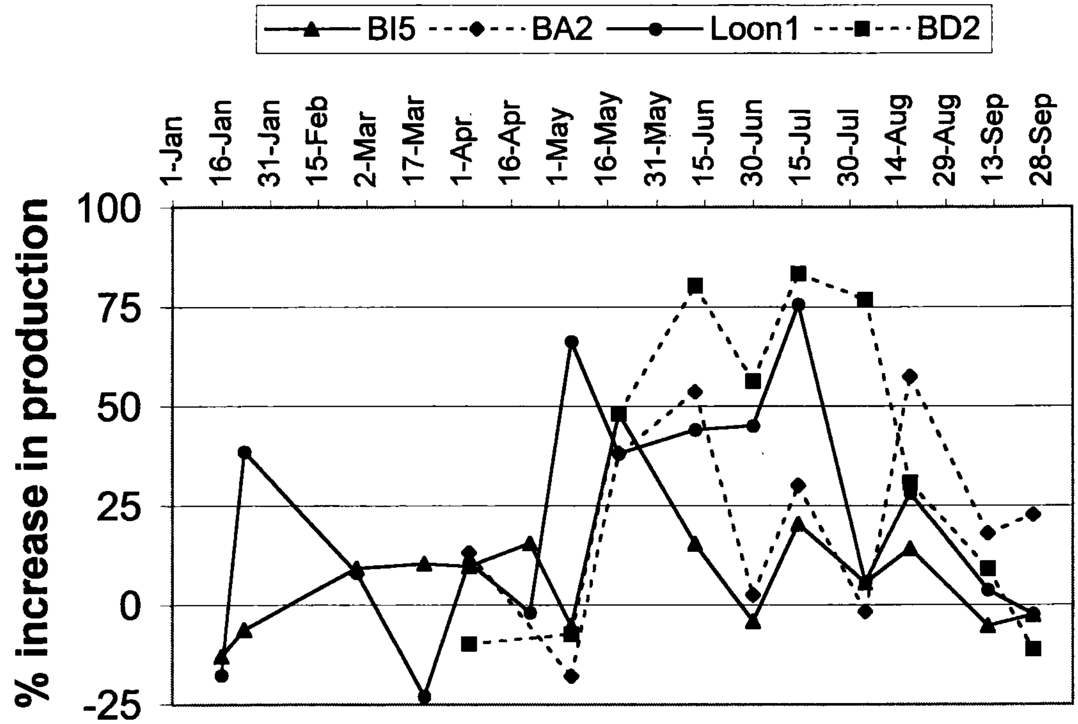

Figure 12. The percent increase in ambient primary production found in the treatment with nutrient spike addition.

The individual values for these experiments are listed in Table 3. The observed winter–spring increases ranged 63–174 mg C m^{-3} d^{-1}. The method has a precision of at least 20 mg C m^{-3} d^{-1}. Increases greater than 30 mg C m^{-3} d^{-1} are likely to be above experimental noise. There are times when the nutrient spike treatment produced less carbon than the ambient and this was, interestingly, most prevalent in the surface samples of BI-5. A mechanism for this result is not known.

The production increases were recorded on sunny days (27 Feb 97 and 3 Apr 97), as would be expected since we observe production to be highly correlated with solar radiation. In one case (20 Mar 97) there was high incident radiation, but strong runoff with high amounts of suspended sediments reduced water transparency substantially. In most cases, however, we could expect that increased production could be sustained for the period of a crisp, clear, sunny weather pattern that often occurs in our region in winter/early spring.

In order to help assess the impact of adding nutrients to Budd Inlet in wintertime, the duration of sunny wintertime weather patterns should be determined. Then, the maximum carbon production increases as indicated by this study (i.e., 50–200 mg C m^{-3} d^{-1}) should be scaled to the duration of sunny wintertime weather patterns. This carbon quantity should be modeled within the system to reflect the reduction of oxygen concentration in order to investigate water quality effects (lowering of DO by >0.2 mg/L) to inner Budd Inlet.

Table 3. Effect of nutrient spike on primary production obtained from Budd Inlet. Bold indicates production change greater than 30 mg C m^{-2} d^{-1} or than 25%.

Expt #	Date	Station	Ambient integrated PP (mg C m^{-2} d^{-1})	Spiked integrated PP (mg C m^{-2} d^{-1})	Delta production (mg C m^{-2} d^{-1})	% change
1	16-Jan-97	BI-5	46	40	-6	-13
		Loon-1	67	55	-12	-18
2	23-Jan-97	BI-5	32	30	-2	-6
		Loon-1	57	79	22	**39**
3	27-Feb-97	BI-5	700	764	**64**	9
		Loon-1	779	842	**63**	8
4	20-Mar-97	BI-5	6	6	0	7
		Loon-1	29	22	-7	-23
5	3-Apr-97	BI-5	1255	1376	**121**	10
		BA-2	1331	1505	**174**	13
		Loon-1	1185	1311	**126**	11
		BD-2	1155	1041	**-114**	-10
6	22-Apr-97	BI-5	428	494	**66**	15
		Loon-1	996	977	-19	-2
7	5-May-97	BI-5	4235	4012	**-223**	-5
		BA-2	3319	2717	**-603**	-18
		Loon-1	3687	6132	**2445**	**66**
		BD-2	2678	2481	**-197**	-7
8	19-May-97	BI-5	1662	2461	**799**	**48**
		BA-2	1291	1502	**211**	16
		Loon-1	1075	1485	**410**	**38**
		BD-2	1345	1638	**293**	22
9	12-Jun-97	BI-5	3692	4255	**563**	15
		BA-2	1685	2588	**903**	**54**
		Loon-1	1931	2782	**851**	**44**
		BD-2	1565	2821	**1256**	**80**
10	30-Jun-97	BI-5	2601	2492	**-109**	-4
		BA-2	2342	2399	**57**	2
		Loon-1	1459	2117	**658**	**45**
		BD-2	2322	3628	**1306**	**56**
11	14-Jul-97	BI-5	2639	3535	**896**	**34**
		BA-2	3963	5154	**1191**	**30**
		Loon-1	1856	3260	**1404**	**76**
		BD-2	1896	3476	**1580**	**83**
12	4-Aug-97	BI-5	4448	4693	**245**	6
		BA-2	5325	5228	**-97**	-2
		Loon-1	5679	5996	**317**	6
		BD-2	2736	4838	**2102**	**77**
13	18-Aug-97	BI-5	1719	1959	**240**	14
		BA-2	2394	3771	**1377**	**58**
		Loon-1	2951	3781	**830**	**28**
		BD-2	2758	3605	**847**	**31**
14	11-Sep-97	BI-5	446	422	-24	-5
		BA-2	1098	1295	**197**	18
		Loon-1	1406	1458	**52**	4
		BD-2	716	780	**64**	9
15	25-Sep-97	BI-5	996	970	-26	-3
		BA-2	715	877	**162**	23
		Loon-1	2676	2613	**-63**	-2
		BD-2	2282	2026	**-256**	-11

Other Important Considerations

The focus of the Budd Inlet Science Study was on quantifying carbon production from phytoplankton and following the cycles of nutrients and oxygen. However, it should be noted that qualitative changes to the phytoplankton community could be possible from added nutrient supply.

Little is known regarding what controls phytoplankton species composition and succession. Diatoms are the primary phytoplankton group in Budd Inlet throughout most of the year; however, dinoflagellates can be numerically dominant in summer (Eisner and Newton, 1997). Harmful forms of phytoplankton (*Pseudonitschia* spp. leading to amnesiac shellfish poisoning, *Heterosigma carterae* leading to fish kills, *Alexandrium catenella* leading to paralytic shellfish poisoning) have been observed in Budd Inlet (Eisner and Newton, 1997). The stimulus for a particular species to bloom is not known; however, nutrient dynamics are suspected in having a role in determining phytoplankton species succession (Justic et al., 1995; Conley and Malone, 1992; Hecky and Kilham, 1988; Officer and Ryther, 1980). The importance of such a mechanism during winter is not known, though it would likely be much lower than in summer.

One influencing factor on phytoplankton species shifts due to eutrophication has been the N:P (nitrogen/ phophoruss) ratio (refs). In nature, nitrogen and phosphorus are taken up by phytoplankton at a ratio of 16 to 1 (Redfield et al., 1963). When nutrients are added from anthropogenic sources, often the ratio is skewed significantly. This, in addition to the exact form of the nutrients (e.g., dissolved organic nitrogen vs. ammonium vs. nitrate) can be a determinant in phytoplankton species selection. Although the knowledge on this subject is incomplete and is difficult to obtain, additions of nutrients closer to the Redfield ratio of 16:1 would hold less risk of upsetting natural communities.

Summary of Observations

- Budd Inlet has very high primary productivity relative to other Puget Sound locations.
- A marked seasonal range in primary production was evident in 1997, but summertime lows were not seen.
- The highest production shifted from the Inner Inlet (May–June) to the mid-inlet (July–Sept), and this may be driven by patterns in biomass distribution.
- Light was a significant determinant of winter production levels.
- Added nutrients increased production year-round. Although the effect was smaller in winter, it was observed to be as high as a 35% increase.

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Benthic Oxygen Demand and Nutrient Fluxes in Budd Inlet

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Introduction

Knowledge of sedimentary processes is important in order to understand the dynamics of a water body because the sediments act as both a source and sink for organic and inorganic materials. In all water bodies, gravity acts on both organic and inorganic particulate material, and particulate material that is not advected out of an inlet or decomposed in the water column eventually settles to the sediments, where it is either permanently buried or remineralized. The deeper the inlet, the more time is available for settling material to be decomposed in the water column and the lower the amount reaching the sediments,and vice versa. Consequently, in shallow water bodies like Budd Inlet the sediments take on a quantitatively important role in organic matter and nutrient cycling.

Of primary importance to the health and productivity of a body of water are dissolved oxygen and inorganic nutrient concentrations. Sedimentary decomposition of organic matter removes oxygen from the overlying waters and recycles inorganic nutrients back into the water column (Berner, 1980). In particular, nitrogen is important because it is most often the nutrient limiting phytoplankton production in marine environments (Ryther and Dunstan, 1971). Nitrogen is also often introduced into coastal waters as a result of anthropogenic activities and frequently results in euthropication. Within the sediments, combined nitrogen (primarily NO_3, NH_4 and organic-N) is either remineralized and returned to the water column, i.e., recycled, or, under anoxic conditions, is denitrified to N_2 gas which diffuses out of the sediments and is ultimately lost to the atmosphere.

This study of sediment-water interactions was undertaken as part of an effort to evaluate alternatives for wastewater disposal in the area bordering Budd Inlet in southern Puget Sound. The overall objectives of the Budd Inlet sediment study were to:

1) measure the sediment oxygen consumption rate and determine its importance in regulating water column dissolved oxygen levels;
2) determine and understand the role of the sediments in nutrient cycling in the inlet, especially nitrogen cycling; and
3) support development of a dynamic sediment model to be used in conjunction with the water-column model to analyze development.

Methods

Benthic conditions were monitored over the course of a year at four locations throughout Budd Inlet in southern Puget Sound. Samples were collected approximately twice a month from September 1996 through September 1997. Locations of each station and approximate depths are shown in Figure 1. Station A was located in roughly 10 m of water in the dredged turning basin of the inner inlet, and was the closest station to Capitol Lake. Station B was the shallowest of the four stations, with a Mean Lower Low Water (MLLW) depth of two meters, and was the only station where the sediments and bottom water were within the euphotic zone. Station C was approximately 10 m deep and located more or less equidistant between the east and west boundaries of the inlet, as well as between the north and south boundaries of the inlet. Station D was about 15 m deep, closest to the mouth of the inlet, and thus closest to the rest of Puget Sound.

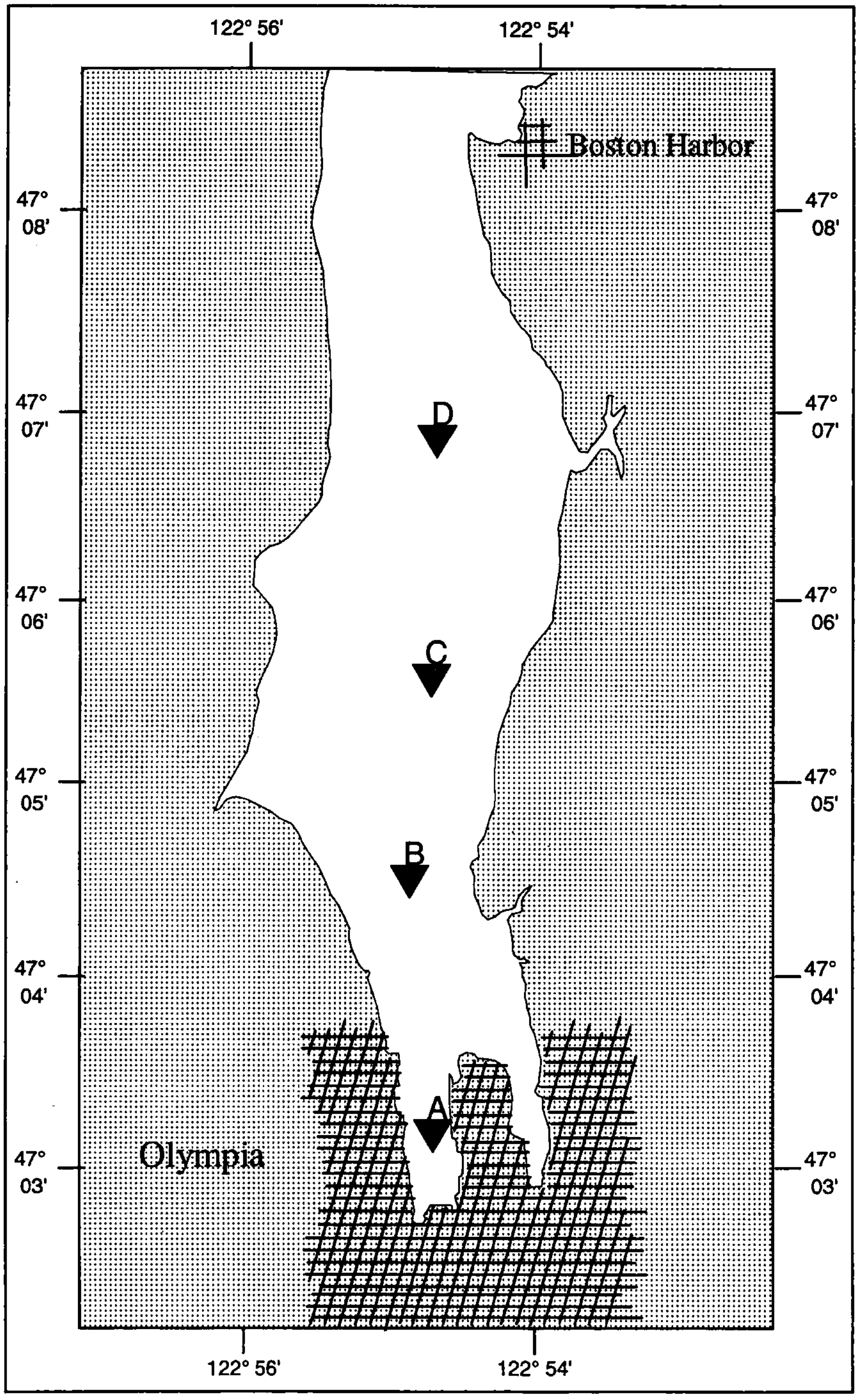

Figure 1. Benthic study station locations in Budd Inlet.

Samples for bottom water concentrations of dissolved oxygen and nitrogen gas, nitrate, ammonium, and silicate were taken using a Niskin bottle during each sampling period. Bottom water temperature and dissolved oxygen were measured using a SeaBird CTD.

In situ benthic chambers (mini-landers) described in Devol et al. (1997) were used to determine the exchange of solutes between the sediments and overlying water. The landers can be envisioned as "bell-jars" that sit on the sediments and enclose a volume of water overlying the sediments for some period of time. By sampling the overlying water as a function of time, benthic fluxes between the sediments and the overlying water can then be calculated. Mini-landers consisted of a stainless steel flux chamber with

an open bottom and a moveable top. With the top open, the mini-landers were implanted in the bottom sediments where the chamber enclosed a 412 cm^2 section of sediment and a volume of overlying water. Shortly after the mini-lander was placed on the sediment, the top of the chamber was closed, thus isolating the entrapped overlying water. At pre-programed times, spring-activated syringes extracted water from the closed box by drawing it through nylon tubing. Water volume inside the box was replaced by water drawn in through another nylon tube connected to the outside of the chamber. Calibrated 5-mL nylon loops were placed in-line between the chamber and the syringe samples and were used for dissolved gas analysis. A known amount of lithium chloride was injected into the box shortly after the lid was closed to calculate the exact volume of overlying water in the chamber, and to ensure that the chamber was free of leaks. Throughout the deployment, water inside the chamber was continuously stirred. All actions of the mini-lander were regulated by a preprogrammed microprocessor attached to the top of the instrument.

Samples were collected at four time-points over the course of each deployment (8–12 hr). After the mini-landers were recovered, all samples were kept on ice and brought to laboratories at the University of Washington where samples for dissolved oxygen and nitrogen were analyzed immediately by gas chromatography. Oxygen and nitrogen were stripped from the 5-mL sample loops with a helium carrier gas. Residual water vapor was removed in a Drierite column prior to the sample entering a Varian gas chromatograph containing a molecular sieve 5A column and Carle thermoconductivity detectors (Devol and Christensen, 1993). Dissolved gas measurements were standardized with air according to Grundmanis and Murray (1992). Water samples for nitrate, ammonium, and silicate were frozen and analyzed at a later date with a Technicon Autoanalyzer using the methods described in Whitledge et al. (1981).

Results

Bottom Water Data

The seasonal trends in bottom water oxygen and nutrient concentrations are shown in Figure 2. Seasonal cycles of oxygen were similar at Stations A, C, and D, where oxygen concentration increased from September to a maximum around March and remained approximately constant through April. In May dissolved oxygen began to decrease at these three stations reaching a minimum in August. Among these three stations this trend was most pronounced nearest the head of the inlet and became more attenuated with distance from the head. The summer minimum oxygen concentrations at Stations A, B, and C were 63, 113, and 197 µM respectively. The exception to this seasonal trend was Station B where oxygen concentrations increased from March to June and reached supersaturated values (up to 427 µM) in July and August.

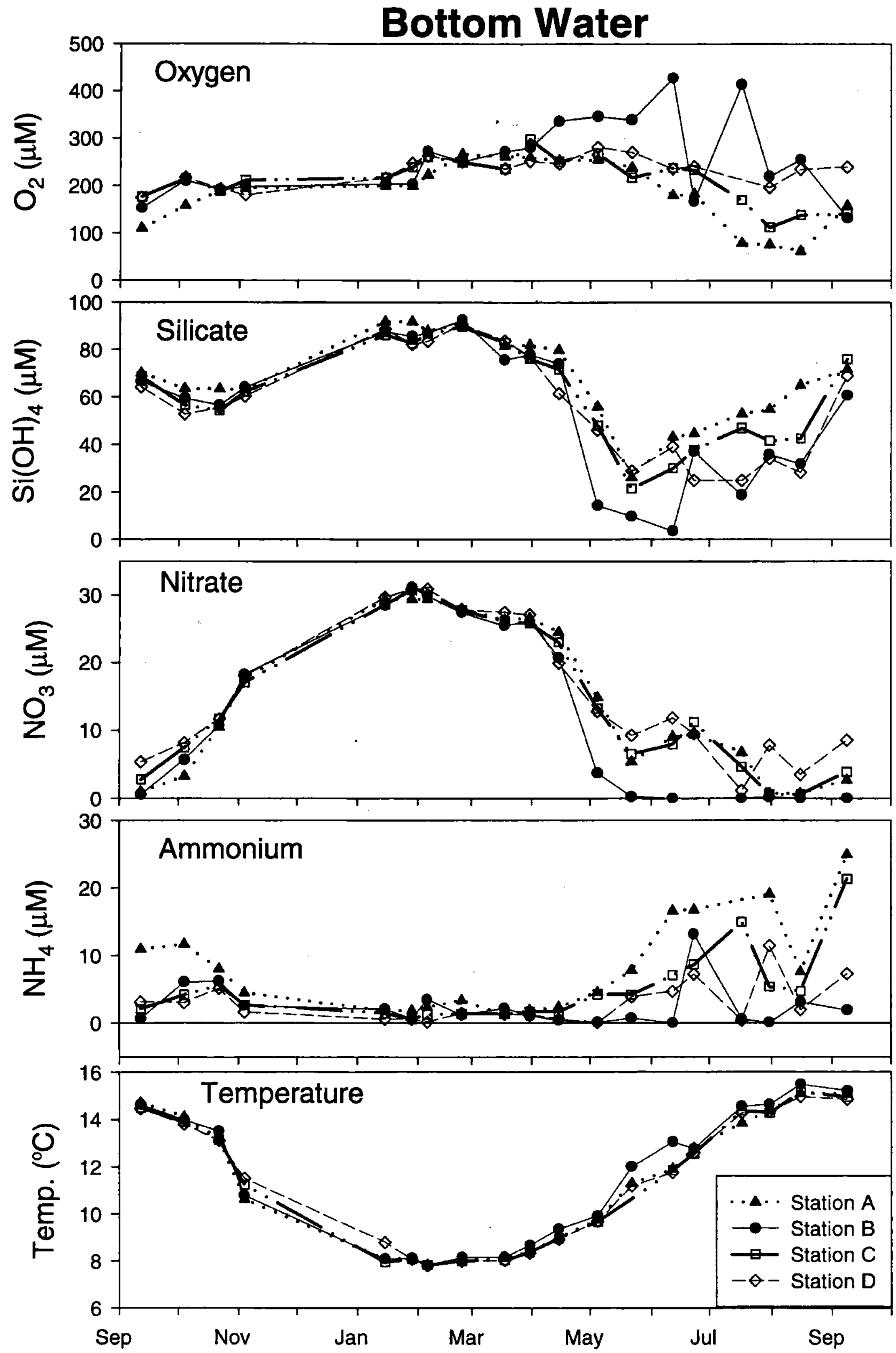

Figure 2. Bottom water temperature, oxygen, silicate, nitrate, and ammonium concentrations.

In September 1997, silicate bottom water concentrations were about 60 µM throughout the inlet. Concentrations at all stations then increased to a maximum of about 90 µM between November and March. With the onset of the spring phytoplankton bloom, silicate concentrations then decreased at all stations. Minimum values at Stations A, C, and D were all approximately 25 µM. Station B minimum silicate concentrations were lower than those at the other stations and approached zero in mid-June. After reaching their seasonal lows, concentrations at all stations began to increase again and returned to levels of ~75 µM by the end of the study.

Temporal trends in nitrate were also similar at all stations, increasing in the fall, reaching maximum values of about 30 öM in early February and then decreasing to summer minimum values near zero. Station B showed the most rapid spring decrease and nitrate was exhausted in early June, but such low levels were not encountered at the other stations until late July. Low nitrate concentrations were maintained at all stations throughout the summer and into fall.

Ammonium concentrations were consistently low during most of the year. However, during the summer, appreciable ammonium concentrations accumulated at all stations in the bottom water. Maximum concentrations of greater than 20 µM were observed at Station A, whereas at most other stations concentrations of about 5 µM were more common.

Temperature displayed the same temporal trend throughout the inlet, with more or less the same temperatures at A, C, and D. The trend at Station B, the shallowest station, was similar in shape and winter (Nov.–mid-March) temperatures were about the same as those at the other stations. Spring, summer and fall bottom water temperatures, however, were significantly warmer than those at the other stations. At all stations minimum temperatures of about 8_C were observed from February through mid-March after which time temperature increased to about 15_C in mid-August (Figure 2).

Flux Data

Benthic flux data were determined at each of the four stations for oxygen, silicate, nitrate, ammonium, and nitrogen gas. Oxygen and ammonium fluxes across the sediment-water interface at each station throughout the year are shown in Figure 3. All oxygen flux values were negative, indicating oxygen was taken up by the sediments from the overlying water, while all ammonium fluxes at each site were positive, signifying NH_4 release from the sediments into the overlying water. While values at each station varied, oxygen fluxes generally decreased during the winter months (November through February) at Stations A, B, and D, while oxygen fluxes at Station C were relatively low throughout this time period. Ammonium fluxes exhibited the same trend of decreasing throughout the winter at each station. At all sites, both oxygen and ammonium fluxes reached minima in early spring and then increased throughout the late spring and summer months. Oxygen flux data from Station A showed the greatest overall variation of the four stations, with a minimum rate of -5 mmoles O_2 m^{-2} d^{-1} in late March and a maximum rate of -35 mmoles O_2 m^{-2} d^{-1} in late July. Station A also had the greatest NH_4 flux (~13 mmoles N m^{-2} d^{-1}) in the late summer. Ammonium flux data from Stations A, B, and D all reached minimum values near zero in late March, while Station C had a slightly greater minimum NH_4 flux values of approximately 1.4 mmoles N m^{-2} d^{-1} on the same date.

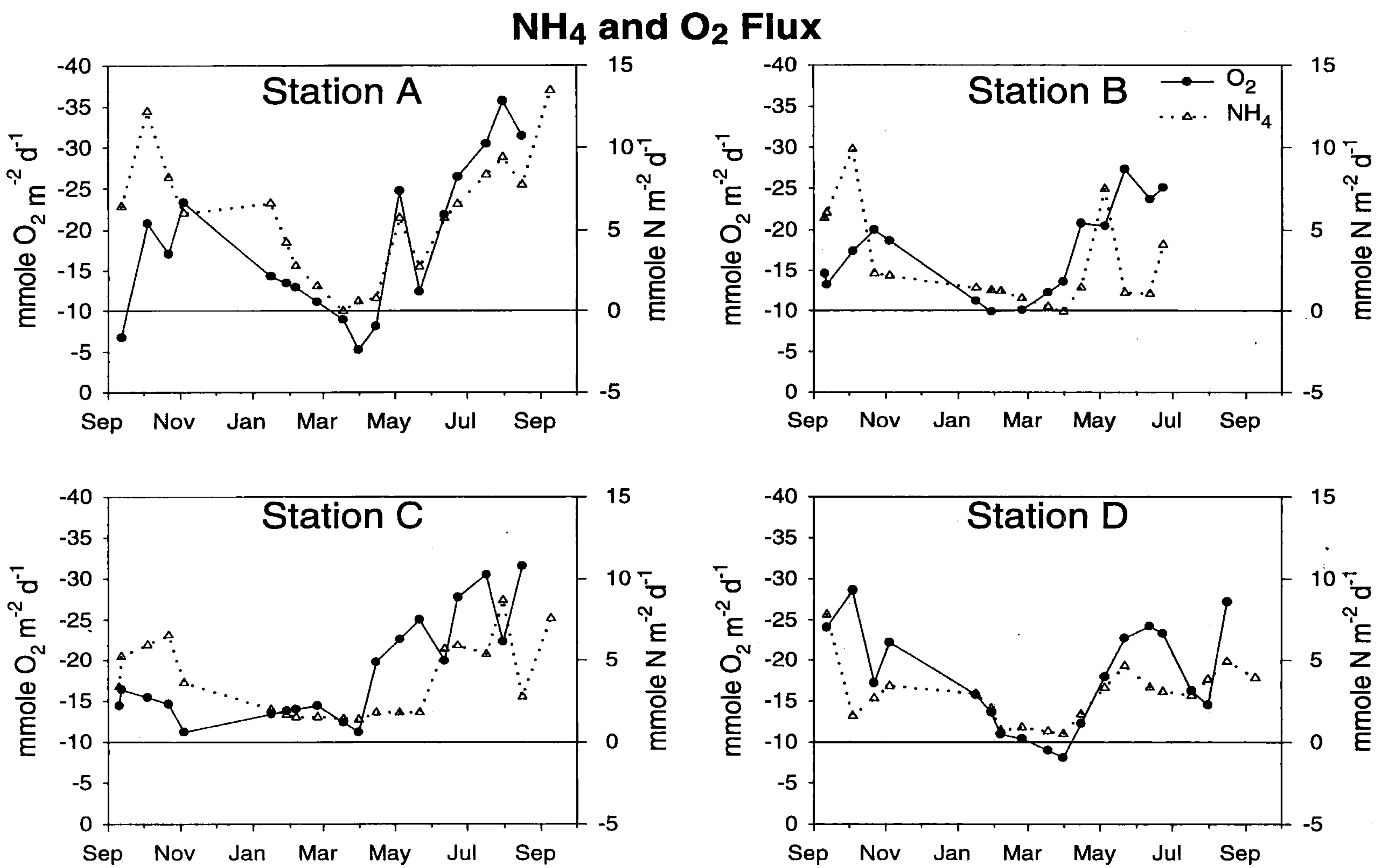

Figure 3. Seasonal ammonium and oxygen benthic fluxes in Budd Inlet. Oxygen fluxes are depicted by solid lines and symbols and are scaled on the left axis. Ammonium fluxes are depicted by dotted lines and open symbols and are scaled on the right axis.

Silicate fluxes (Figure 4) displayed similar annual trends at all stations. In all cases, $Si(OH)_4$ fluxes were from the sediments to the overlying water (positive values). In September values were between 5–10 mmoles Si m^{-2} d^{-1}, after which time they decreased at all stations until minimum rates were reached between late February and late March. Stations A, B and C had minimum $Si(OH)_4$ fluxes approaching zero. The minimum flux at Station D was approximately 3 mmoles Si m^{-2} d^{-1}. After reaching minima, fluxes out of the sediments at all stations then increased throughout the summer, and became variable in the early fall, with average values of about 15 mmoles Si.

With a few exceptions nitrate fluxes were generally low throughout the study period at all stations (<3 mmoles N m^{-2} d^{-1}) and fluxes were nearly always from the overlying water into the sediment. Fluxes were measurable by November when nitrate was present in the bottom waters, but fluxes were near zero during periods when bottom water nitrate was near zero (Figure 4).

Nitrogen gas flux data are more sparse than the other flux data, but generally averaged between 2 and 4 mmoles N_2 m^{-2} d^{-1}. The most complete record was obtained at Station C and showed a pattern similar to the other fluxes with relatively higher fluxes in the summer fall periods and generally low values during the winter.

Discussion

Annual trends in the bottom water oxygen, silicate, ammonium, and nitrate concentrations in Budd Inlet are dominated by the biogeochemical processes within the inlet and mixing with south Puget Sound waters across the mouth of the inlet. Thus, during the winter when both Budd Inlet and south Puget Sound are well mixed vertically and biological production is at a minimum, bottom water oxygen concentrations are near atmospheric equilibrium saturation, and the other dissolved species reflect the winter conditions in the main basin of south Puget Sound. Throughout the rest of the year the benthic study stations fall into two groups: deep stations (A, C, and D) having depths greater than the euphotic zone depth, and shallow stations (B) having bottom sediments within the euphotic zone. At the deep stations oxygen concentrations were near the saturation value in winter and as the spring bloom progressed beginning around March (J. Newton, personal communication) bottom water oxygen concentrations decreased due to organic matter decomposition of the settling plankton bloom in both the water column and the sediments. At the shallow stations, the trend was the opposite, with supersaturation of oxygen accompanying the bloom due to photo synthetic oxygen production within the euphotic zone. It is noteworthy that among the deep stations, the amount of oxygen depletion was greatest near the head of Budd Inlet and decreased toward the mouth, presumably resulting from progressively more influence of mixing with well-oxygenated south Puget Sound waters.

At all stations, both nitrate and silicate were removed from the bottom water as a result of the spring phytoplankton bloom. At the shallow station, the depletion was more rapid and more complete than at the other stations, with bottom water values approaching zero in May and June. This depletion at Station B probably resulted largely from processes taking place within Budd Inlet. Although the same trend of decreasing concentrations was observed at the deep stations, because these waters were below the euphotic zone, much of this was probably a reflection of seasonal processes taking place in south Puget Sound.

Ammonium is usually a transient form of nitrogen in marine environments. It is produced by the decomposition of organic matter and once formed it is either oxidized to nitrate by nitrifying bacteria or, if it is within the euphotic zone, it is taken up by phytoplankton as part of organic matter synthesis. The fact that is was present in the bottom water during the summer at all stations suggests a near-bottom source, and thus is likely the result of sedimentary decomposition of organic matter.

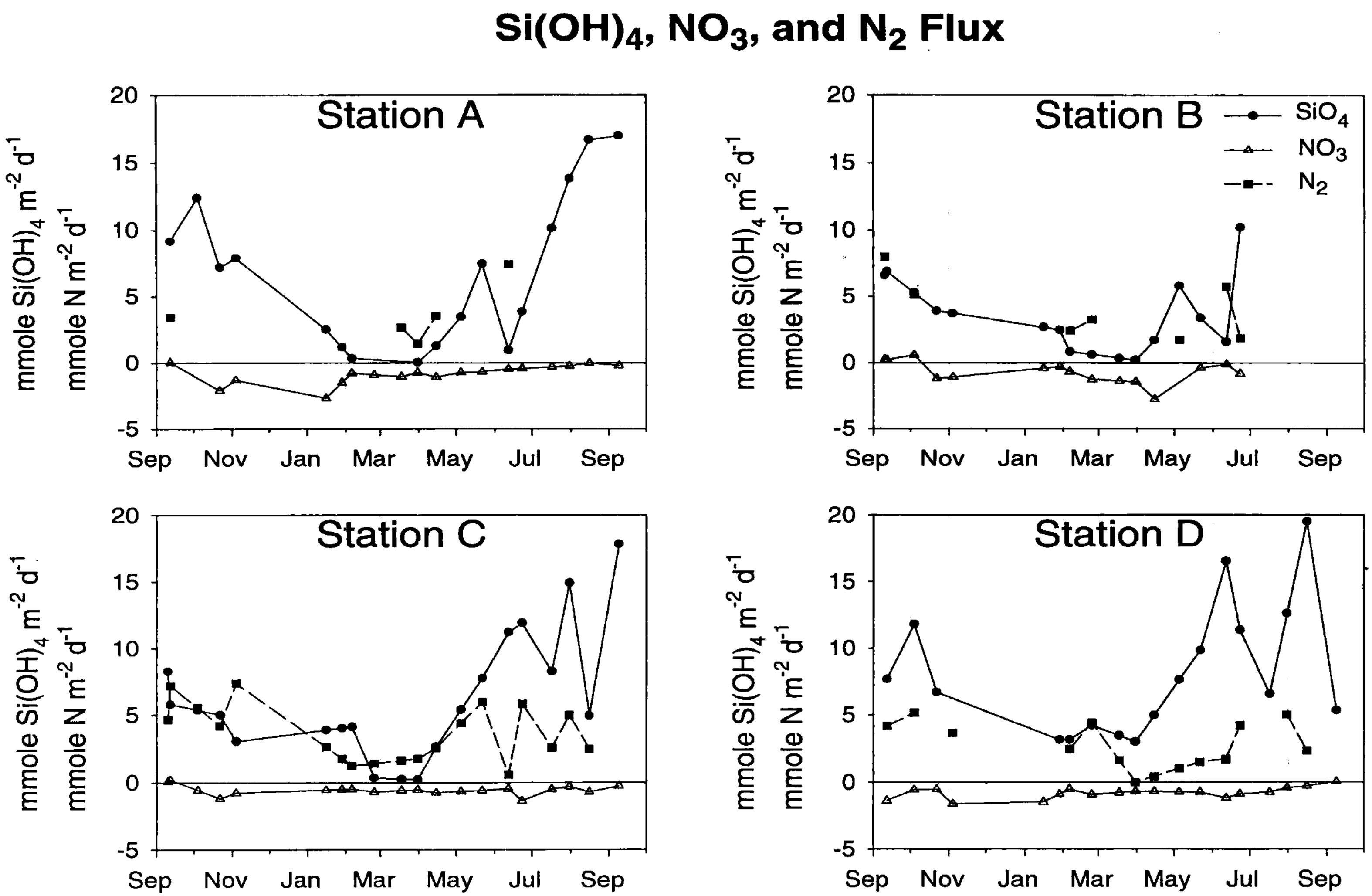

Figure 4. Seasonal silicate, nitrate, and nitrogen gas fluxes in Budd Inlet. Silicate fluxes are depicted by solid circles. Nitrate fluxes are depicted by open triangles. Nitrogen gas fluxes are depicted by solid squares.

Like bottom water nutrient concentrations, sediment fluxes also reflect seasonal cycles. Oxygen fluxes at each station increased in the spring and summer as the spring phytoplankton bloom progressed and new organic matter settled to the sediments. As productivity decreased in the fall and winter, less labile organic matter was transported to and decomposed in the sediments, which was reflected by the low oxygen fluxes during that time (Figure 3). The range in benthic oxygen fluxes in Budd Inlet was between about -5 and -35 mmoles O_2 m^{-2} d^{-1}. These values can be compared to values in Dabob Bay (Hood Canal) that were typically -3 to -8 mmoles O_2 m^{-2} d^{-1} with a maximum of -12 mmoles O_2 m^{-2} d^{-1} (Devol, unpublished data). Similarly, benthic oxygen fluxes on the Washington continental shelf during the summer are typically about -12 mmoles O_2 m^{-2} d^{-1} (Devol and Christensen, 1993). At least some of the difference between Budd Inlet and the other two areas can be ascribed to depth and temperature. At both the Dabob Bay and Washington shelf sites, bottom water temperatures remained constant at about 8 %C throughout the year, while Budd Inlet bottom waters reached 15 %C in the summer months. Additionally, the Dabob Bay site was ~100 m deep and the Washington Shelf stations were located within the 100–200 m depth range. At these deeper stations, more of the settling organic matter was decomposed in the water column, thus leaving less to fuel benthic processes.

Silicate fluxes were similar to oxygen fluxes in that they were largely reflected of the seasonal phytoplankton cycle. As diatom production increased and diatom tests settled to the bottom where they dissolved, silicate fluxes out of the sediments increased. In the fall and winter, diatom populations decreased and there was a resultant decrease in the silicate flux out of the sediments.

Although nitrate fluxes displayed little seasonality, the direction of the flux (into the sediments) indicates that oxygen was consumed relatively rapidly within the sediments, and the anoxic process of denitrification was important. The importance of denitrification in the sediments was confirmed by the observed N_2 flux out of the sediments (Figure 4). Ammonium is remineralized as a result of sedimentary decomposition of organic matter. As with oxygen and silicate, NH_4 fluxes increased in the summer resulting from increased input and degradation of organic matter, and decreased in the winter when production, transport, and decomposition slowed (Figure 3).

One of the main objectives of this study was to evaluate the influence of sediments on the water-column oxygen concentration. Calculated and observed summertime water-column oxygen depletion rates at Stations A, C, and D are shown in Table 1. Given an average bottom water oxygen concentration of 187 mM at Station A, and a calculated oxygen depletion rate of 2.9 μmole O_2 L^{-1} d^{-1}, the sediments would be capable of depleting all of the oxygen in the water column in 64 days. Similarly, it would take 77 and 149 days at Stations C and D, respectively, for the sediments to reduce the oxygen concentration to zero. Thus, the sediments appear to play a potentially important role in regulating water-column oxygen concentration. It is also interesting to compare observed daily oxygen depletion rates (from bottom water concentrations over time) to calculated daily oxygen depletion rates. Station A observed daily oxygen depletion rates were 2.1 μmole O_2 L^{-1} d^{-1} during the summer. This decrease reflects both sediment and water-column respiration, as well as an oxygen replenishment from horizontal exchange with more oxygenated water. Taking those factors into account, a calculated oxygen depletion rate of 2.9 μmole O_2 L^{-1} d^{-1} by the sediments is a significant loss term. Station C had an observed bottom water oxygen depletion rate of 1.5 μmole O_2 L^{-1} d^{-1} and a calculated oxygen depletion rate of 2.8 μmole O_2 L^{-1} d^{-1} in the summer. Similar fluxes at Stations A and C could result from the similar depth at the two stations. Station D, which was deeper, had a lower observed bottom water depletion rate (1.1 μmole O_2 L^{-1} d^{-1}) as well as a lower calculated depletion rate (1.6 μmole O_2 L^{-1} d^{-1}) than the other stations.

These calculations show that the observed bottom water oxygen depletion rate is higher, resulting in a faster depletion time, in the inner inlet where the sediments are slightly shallower and there is less contact with oxygenated water from Puget Sound. Since the calculated oxygen depletion rates also generally increase further toward the inner inlet, this suggests that the sediments in the inner inlet exert a greater relative influence on water-column oxygen concentrations than those in the outer inlet.

Table 1. Annual average bottom water oxygen concentrations and summertime oxygen depletion calculations. Calculated O_2 depletion rates were determined by dividing the summertime (May–August) average measured flux (mmoles O_2 m^{-2} d^{-1}) by the MLLW depth (m). Observed bottom water depletion rates were calculated from the observed bottom water concentration change over the same time interval. Calculated O_2 depletion time was, thus, the average bottom water O_2 concentration (μM) divided by the calculated O_2 depletion rate (μmole O_2 L^{-1} d^{-1}). Comparable calculations could not be made for Station B since it is in the euphotic zone and has the additional input of oxygen directly from photosynthesis, and the additional loss due to oxygen evasion.

	Station A	Station C	Station D
Average Bottom Water O_2 Concentration (μM)	187	214	232
Calculated O_2 Depletion Rate (μmole O_2 L^{-1} d^{-1})	2.9	2.8	1.6
Observed Bottom Water O_2 Depletion Rate (μmole O_2 L^{-1} d^{-1})	2.1	1.5	1.1
Calculated Bottom Water O_2 Depletion Time (days)	64	77	149

The second objective of this study was to evaluate the role of sediments in nitrogen cycling in the inlet. Due to the importance of nitrogen as the limiting nutrient for phytoplankton, and to potential future anthropogenic influences, it is essential to understand what sources and sinks contribute to the nitrogen budget in order to develop alternative wastewater management plans. Nitrogen sources to and sinks within the sediments in the inner and the whole inlet are shown in Table 2. In order to evaluate the importance of the sediments to nitrogen loading, we compared NH_4, NO_3, and N_2 fluxes to the total nitrogen loading to the inlet. Total inputs included inputs from Puget Sound, Capitol Lake, LOTT (Lacey-Olympia-Tumwater-Thurston County sewage treatment facility), other waste water treatment plants, sediments, streams, and rainfall (Cox and Giles, 1998).

Table 2. Annual nitrogen sources and sinks in Budd Inlet. The inner inlet is defined as from the head to Station B and includes mean data from Stations A and B. The whole inlet includes data from all stations. Yearly NH_4, NO_3, and N_2 fluxes were calculated by multiplying the average flux at each station by the respective surface area of each inlet section and then by 365 days to convert to a yearly value. All values are given in metric tons y^{-1} (mt y^{-1}) Total N loading consists of all measured nitrogen inputs to the inlet, including Puget Sound, Capitol Lake, LOTT (Lacey-Olympia-Tumwater-Thurston County sewage treatment facility), other wastewater treatment plants, sediments, streams, and rainfall (Cox and Giles, 1998). The NH_4 % of Total is the annual percentage of the total N loading attributed to NH_4 flux from the sediments.

	Surface Area (m^2)	Total N Loading mt yr^{-1}	NH_4 Flux mt yr^{-1}	NH_4 % of Total	NO_3 Flux mt yr^{-1}	N_2 Flux mt yr^{-1}
Inner Inlet	3.9×10^6	1980	101	5	-18	-61
Whole Inlet	2.0×10^7	3350	395	12	-69	-346

Ammonium fluxes comprised the only significant contribution of the sediments to the inlet, averaging 12% of the total nitrogen loading to the whole inlet. Nitrate fluxes into the sediments and nitrogen gas fluxes out of the sediments, which eventually result in N_2 being lost to the atmosphere, were both sinks attributed to the sediments. (Note, however, that the NO_3 flux into the sediments is converted to N_2 by denitrification, so it is a component of the N_2 flux out). Nitrogen gas flux values were on the same order as ammonium fluxes, signifying the importance of denitrification in the inlet. Similarly, on the Washington Shelf NH_4 fluxes were comparable to N_2 fluxes (Devol and Christensen, 1993). Remembering that the NH_4 flux out of the sediments represents recycling and that the N_2 flux represents loss, the sediments appear to be responsible for cycling about 22% of the nitrogen loading to the inlet

[(395+346)/3350].

In summary, this study strongly suggests that the sediments play an important role in the biogeochemical processes of Budd Inlet. Benthic oxygen fluxes in Budd Inlet were higher than fluxes found in other regional studies, probably due to Budd Inlet's shallower depths and the higher temperatures. Given the measured oxygen flux values, and the observed bottom water oxygen depletion rates, the sediments appear to be important in regulating water-column oxygen concentration, especially toward the head of the inlet. Similarly, benthic fluxes of various nitrogen species appear to play a significant role in the nitrogen cycling in Budd Inlet. Ammonium fluxes from the sediments to the overlying water in the whole inlet comprised 12% of the total annual nitrogen loading. Denitrification within the sediments, which was on the same order (but in the opposite direction) of NH_4 fluxes, was also a significant nitrogen sink in the inlet.

Acknowledgments

This study was supported by the LOTT Partnership (Lacey Olympia Tumwater Thurston County). The authors wish to express thanks to Dean Lambourn for maintaining operation of the mini-landers, Chuck Boatman for helpful suggestions throughout the project, and Eric Noah for assistance in all aspects of the field work. We also thank Jeff Christian of Columbia Analytical Services, and Kathy Krogslund of the University of Washington for help with analytical analyzes.

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Determination of Seasonal Trends for Carbon, Nitrogen, Pigments, and Sediment Resuspension Rates in Budd Inlet using Moored Sediment Traps

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Abstract

To evaluate the spatial temporal distribution of organic carbon, nitrogen, and pigments associated with particulates in Budd Inlet, moored sediment traps were deployed 1 m above the bottom at six locations in Budd Inlet from October 1996 to October 1997. High-resolution (biweekly) sampling occurred for carbon, nitrogen, and pigments, producing a data set capable of distinguishing short-term episodic events in the inlet. Short-term sampling of pigments was used to estimate losses of phytoplankton from sinking and grazing. Long-term (bimonthly) sampling was used to determine sediment accumulation rates, biogenic silica concentrations, and Pb-210 and Ra-226 activities. Near-surface traps (biweekly sampling) were deployed to estimate the carbon and nitrogen flux produced by phytoplankton.

Bottom sediment resuspension rates were also determined using three independent methods: comparison of gross and net sedimentation rates, biogenic silica flux mass balance, and mass balance of carbon and nitrogen. The latter techniques required deployment of the surface sediment traps. Excellent agreement was observed between all three methods.

The sediment trap data collected proved to be a critical component of the overall Budd Inlet Study goal to develop a scientific understanding and working model of phytoplankton dynamics and nutrient transport/recycling in the inlet.

Modeling Nutrient Dynamics and Eutrophication Potential in Budd Inlet

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John E. Edinger
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Abstract

An integrated 3-D numerical hydrodynamics and water quality model is being developed and applied to Budd Inlet. The objective of the modeling is to assess potential impacts on the water quality in Budd Inlet related to the present and projected additional discharge from the LOTT wastewater treatment facility, which discharges into the head of Budd Inlet. Current population estimates show that the presently permitted treatment plant flows may be exceeded during wet-weather winter months within the next seven years. If Budd Inlet could assimilate greater effluent loads during wet weather without significantly impacting water quality, then LOTT may be able to utilize existing unused treatment plant capacity as part of their overall wastewater management strategy, resulting in potentially significant cost savings to the rate payers.

Chronic low dissolved oxygen conditions that occur in the near-bottom waters within Budd Inlet in the summer and early fall were identified as the water quality condition of most concern and are the focus of the modeling effort. Key questions to be addressed by the modeling include:

- Can the effluent discharge be increased above the present permit limit during wet weather months without adversely impacting water quality?
- Could the present permit condition requiring nitrogen removal during spring, summer and early fall be changed without adversely impacting water quality?
- What is LOTT's contribution to the summertime low dissolved oxygen conditions?

We will present an overview of the modeling approach and the key findings.

PUGET SOUND RESEARCH '98

SESSION 1C

PUGET SOUND SEAFOOD—THE HUMAN HEALTH LINK

Session Chair:

Duane Fagergren
Puget Sound Water Quality Action Team

Status and Trends in Fecal Coliform Contamination in Puget Sound Embayments

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Office of Shellfish Programs, Washington State Department of Health

Introduction

The Washington Department of Health (DOH) is mandated to protect the health of shellfish consumers from fecal contamination from humans and other warm-blooded animals. DOH monitors fecal coliform levels at over a hundred intertidal and subtidal commercial shellfish growing areas throughout Western Washington and classifies them according to their fitness for harvest.

The Department of Health participates in the Puget Sound Ambient Monitoring Program (PSAMP). An important goal of PSAMP is "to measure the success of programs implemented under the Puget Sound Water Quality Management Plan" (DOH 1995). DOH data from shellfish growing areas might address this and other PSAMP goals. This technical report addresses two questions: 1) whether fecal coliform levels have changed in PSAMP shellfish areas; and 2) whether trends are related to human activities.

Numerous watershed studies have shown how fecal pollution contaminates shellfish growing areas via several pathways (storm runoff, malfunctioning sewage treatment plants and failed individual onsite sewage systems, combined sewer overflows, faulty farm practices, boat waste, etc.). Considerable effort has been spent on pollution control in a number of Puget Sound watersheds. Remedial action has included (to greater or lesser degrees): 1) agricultural best management practices; 2) inspection and repair of failed individual on-site sewage systems; 3) low-cost loans for those with limited incomes to repair their on-site systems; 4) replacement or repair of sewage collection and treatment facilities; and 5) construction of stormwater treatment facilities.

In 1988 DOH selected nine growing areas for long-term PSAMP monitoring (Figure 1). Seven of the nine areas and their associated watersheds have been the focus of watershed planning and nonpoint source cleanup over the years. Two relatively undeveloped growing areas (Port Blakely and East Sound) serve as controls.

Methods

DOH uses a systematic random sampling strategy (ISSC 1995) to sample shellfish areas. Numerous sites within each growing area are regularly sampled. The sampling frequency depends on the DOH classification. "Approved" areas are sampled six times a year. "Conditionally Approved" areas are sampled monthly. Surface samples for fecal coliform analysis are collected at each site according to APHA (1984). Fecal coliform samples are packed on ice and sent to the W.R. Geidt Public Health Laboratory in Seattle. Analyses are run within 30 hours of collection. Fecal coliforms are analyzed with the multiple tube fermentation procedure using A-1 broth (Method 9221 E; APHA 1995). Surface measurements of salinity and temperature are also taken, in addition to tide and weather conditions.

Standards and Criteria

ISSC (1995) specifies a fecal coliform standard (based on systematic random sampling) as follows:

Criterion 1: Fecal colforms levels in samples shall not exceed a geomeric mean value of 14 organisms per 100ml.

Criterion 2: The estimated ninetieth percentile of fecal coliform samples shall not exceed 43 MPN per 100ml.

(Note: in order to comply with the growing area standard, both criteria must be met.)

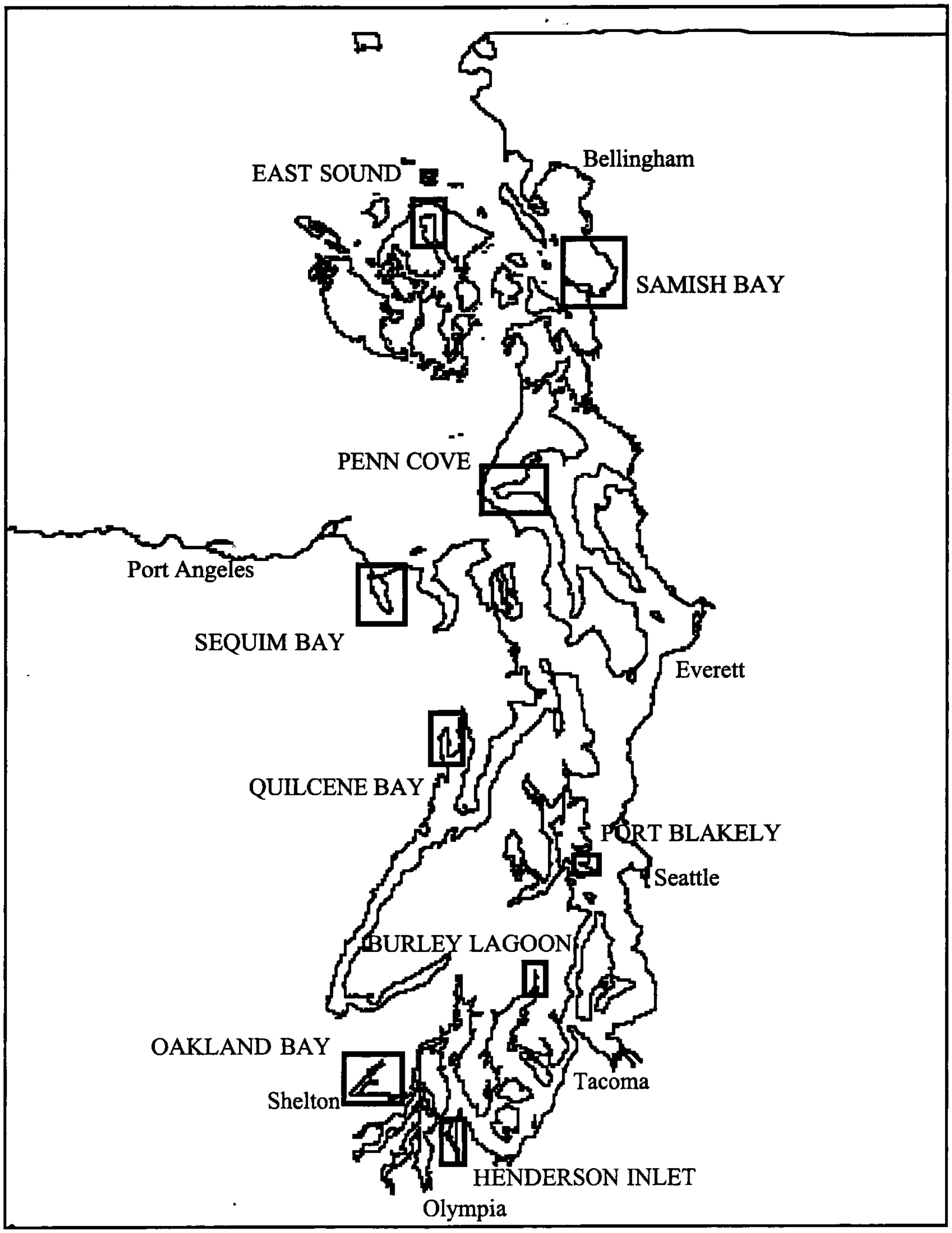

Figure 1. Nine shellfish growing areas selected for long-term monitoring for the Puget Sound Ambient Monitoring Program (PSAMP).

The NSSP protocol requires a minimum of 30 previous results to calculate the criteria. In other words, on any particular sampling date of interest, criteria are calculated from a minimum of 30 samples collected prior to that date. This means that in the case of "Conditionally Approved" areas (sampled once a month), nearly three years of data go into each calculation. In the case of "Approved" areas (sampled six times a year), nearly six years of data are included. These long periods effectively reduce variation inherent with fecal coliform data. Although ISSC (1995) requires a minimum of 30 prior results, the PSAMP analysis used a minimum based on full years with complete sets of seasons in order to minimize seasonal effects. For example, criteria for "Conditionally Approved" areas (sampled monthly) were calculated with a maximum of 36 samples to provide complete seasonal coverage.

Data Analysis

Criteria were calculated for sampling dates from the most recent date (end of calendar year 1997) back to a date beyond which the minimum sampling size could not be met. The criteria were then plotted versus time to detect trends. Trends in Criterion 2 (ninetieth percentiles) were tested with Spearman's *rho* and Kendall's *tau* (nonparametric statistical tests based on ranks). Criterion 2 was selected for trend testing because Criterion 2 typically changes more rapidly than Criterion 1 (geometric means). Status was determined on the percentage of dates within the two most recent calendar years (ending 1997) that fell into several compliance categories. As stated earlier, compliance required that both criteria be met.

Results

Henderson Inlet

Henderson Inlet was downgraded from "Approved" to "Conditionally Approved" or "Prohibited" between 1984 and 1985 (DOH 1997). Fecal coliform sources included failed onsite sewage systems, poor animal keeping on small farms, and stormwater generated in the City of Lacey. Since that time the Thurston County Health Department and Thurston Conservation District have facilitated on-site system repairs and best management practices for rural landowners. In 1991 the City of Lacey adopted standards for construction of stormwater facilities for all new developments. A number of facilities have been constructed as part of a regional stormwater management plan.

Twenty sites in Henderson Inlet have been sampled continuously since 1988. Results are summarized in Figure 2. Seventeen stations met the growing area standard on all dates during the most recent two-year interval (i.e., 100% compliance). Three sites (stations 3, 5, and 6) failed to meet the standard at least part of the time. These sites are located in the southern end of the estuary where watershed influence is high and dispersion through tidal exchange is minimal. Trend has been upward at 16 of 20 stations. One station shows a downward trend and three others have not changed significantly.

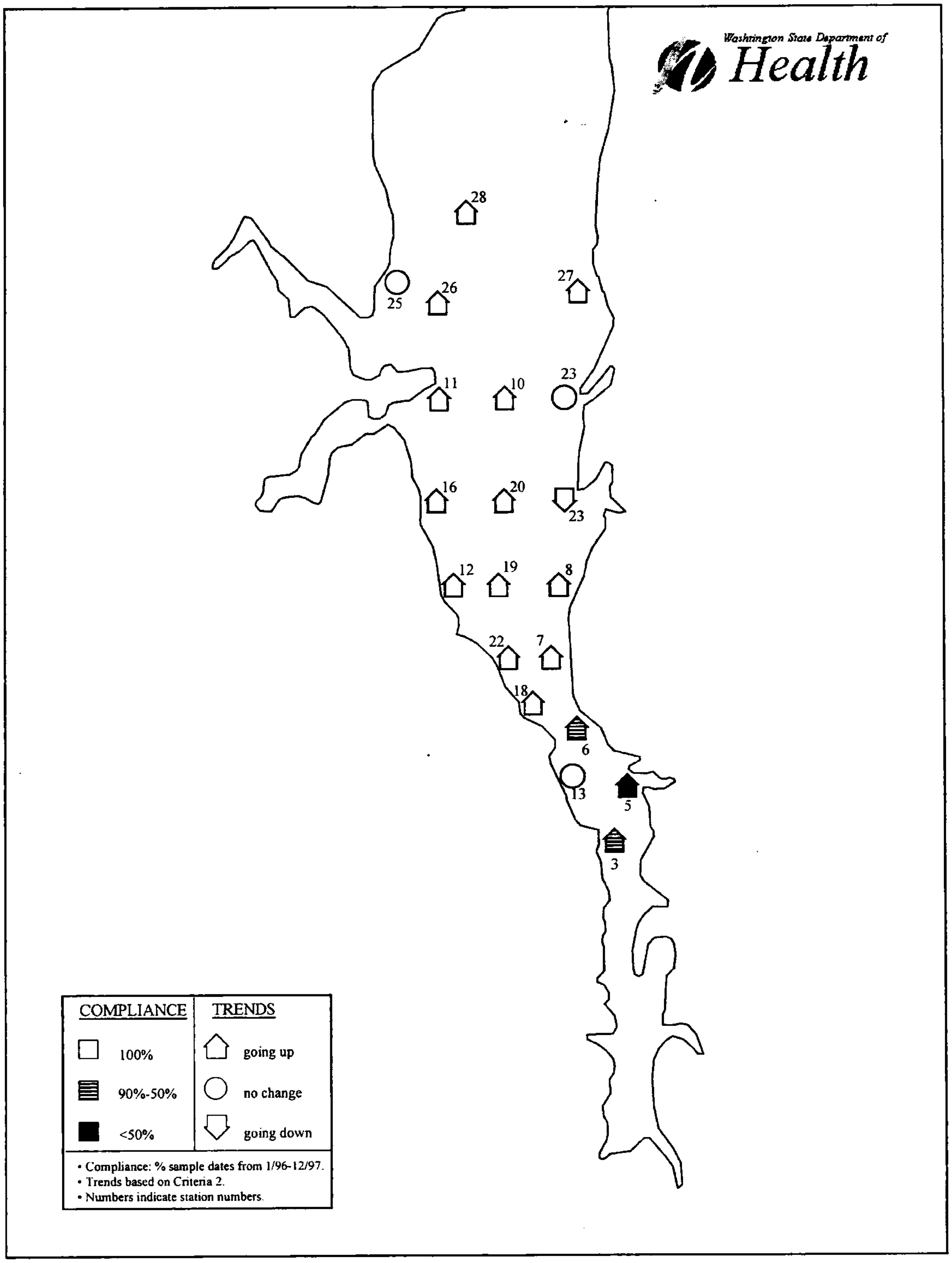

Figure 2. Fecal coliform trends and status in Henderson Inlet

Figure 3 shows plots of growing area criteria for three typical stations. Both criteria show steady upward trends. Note that the rate of change for Criterion 2 (ninetieth percentile) is greater than Criterion 1 (geometric mean). At Station 5, for example, Criterion 2 reached the allowable limit (43 MPN per 100ml) by late 1995. Thus Station 5 failed the growing area standard at that time. Criterion 1 did not reach its allowable limit (14 MPN per 100ml) until late 1997.

The graphs for Stations 11 and 26 are typical of most stations with increasing trends. Although trends are generally upward, the criteria remain within allowable limits. Thus, conditions in Henderson Inlet are generally good, considering the growing population and extent of development in the watershed. However, the slow but steady upward trend in the criteria suggest that control efforts will need to be intensified.

Figure 3. Fecal coliform trends in Henderson Inle

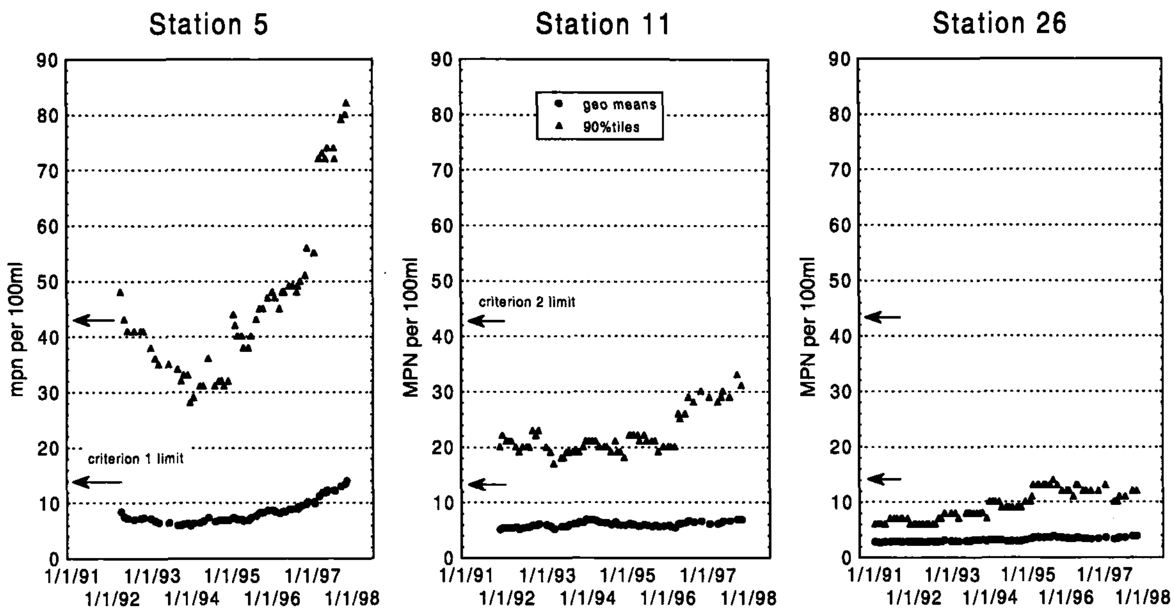

Figure 3. Fecal coliform trends in Henderson Inlet

Oakland Bay

Oakland Bay was downgraded to "Restricted" for shellfish harvest in 1987 (DOH 1997). The major fecal source was inflow and infiltration of stormwater into the sewer system during heavy rains. Sewage overflowed into Oakland Bay and also overloaded the sewage treament plant. During recent years, the city has renovated about half of the system and has expanded service to previously unsewered areas. Oakland Bay was upgraded to "Conditionally Approved" in 1989.

Figure 4 summarizes trends and status in Oakland Bay. All stations complied with the growing area in the most recent two years. Since 1991 Criterion 2 has decreased at nine of 10 sites since 1991, and remained unchanged at one site. The overall reduction may be explained, in part, by the partial renovation of the city's sewer system.

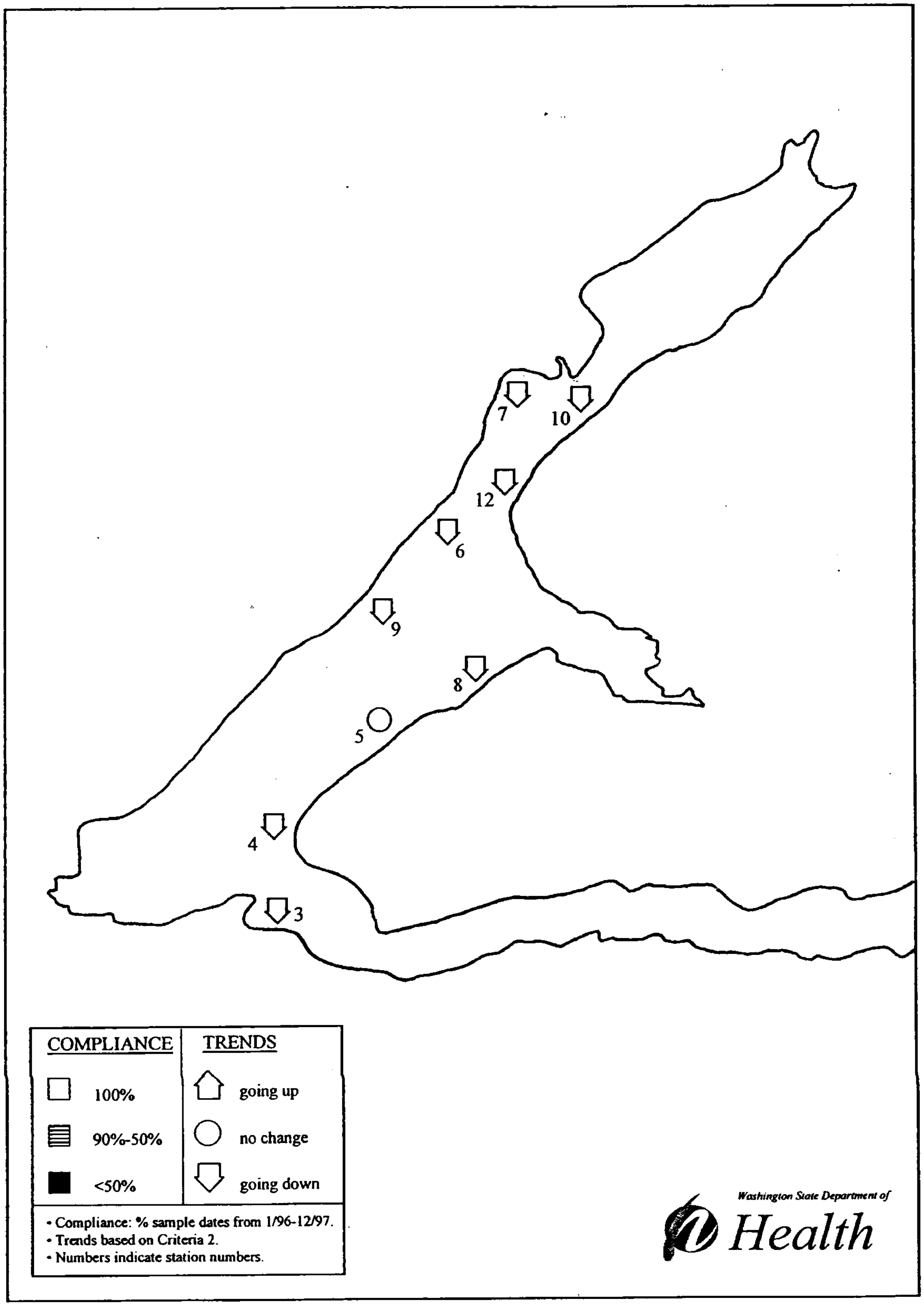

Figure 4. Fecal coliform trends and status in Oakland Bay

Figure 5 shows plots of criteria at three stations in Oakland Bay. The highest fecal coliform levels occurred at Station 3 near the discharge point of the Shelton Sewage Treatment Plant. Fecal coliform contamination has been markedly reduced in recent years. By late 1955, Criterion 2 values were reduced to a quarter of 1992 values. Since that time, Criterion 2 has remained at or slightly below the maximum allowable limit. The continuing renovation project should bring about even more improvement in coming years. However, these improvements must be balanced with the effect of rising population on the capacity of the sewage treatment plant.

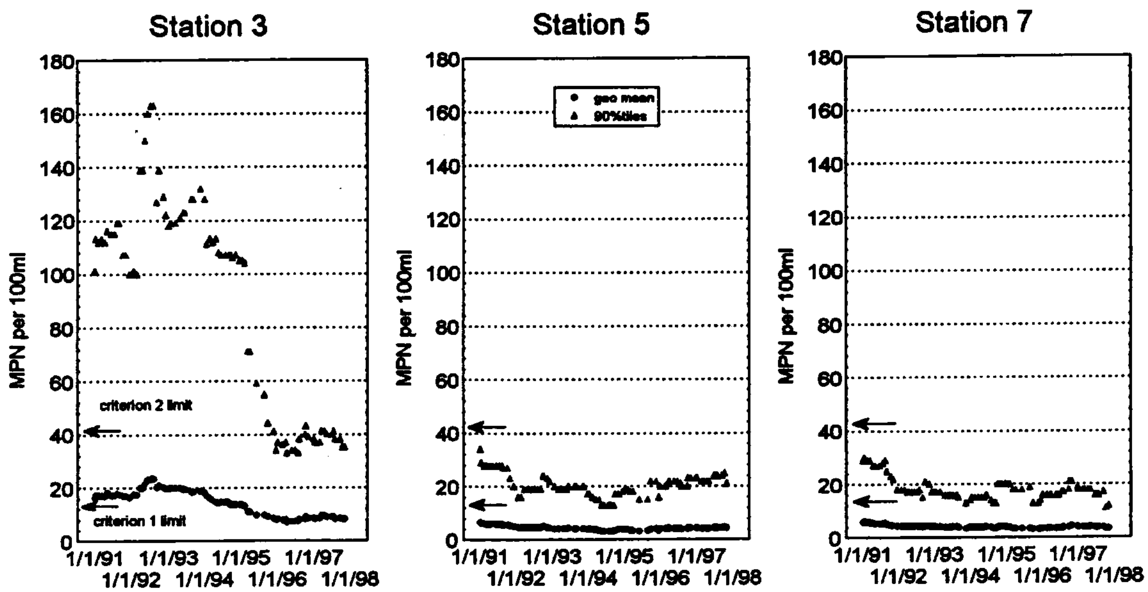

Figure 5. Fecal coliform trends in Oakland Bay

Burley Lagoon

Burley Lagoon was downgraded from "Approved" to "Restricted" in 1981 due to rural nonpoint pollution (DOH 1997). Since 1983, both Kitsap and Pierce county health agencies have inspected and facilitated repair of on-site sewage systems in the watershed. The Kitsap Conservation District has worked with rural landowners to implement best management practices. In addition, several large on-site sewage systems in Purdy have been either rebuilt or connected to a sewer line.

Figure 6 summarizes conditions in Burley Lagoon. Four of five sites complied with the shellfish standard from January 1996 through December 1997. A fifth site failed to meet the growing area standards on 29% of sampling dates during this period. Criterion 2 values increased at the three most southern sites since January 1995. Two other sites remained unchanged. The upward trend in fecal contamination is evidence of the need to continue to search for pollution sources in nearby uplands.

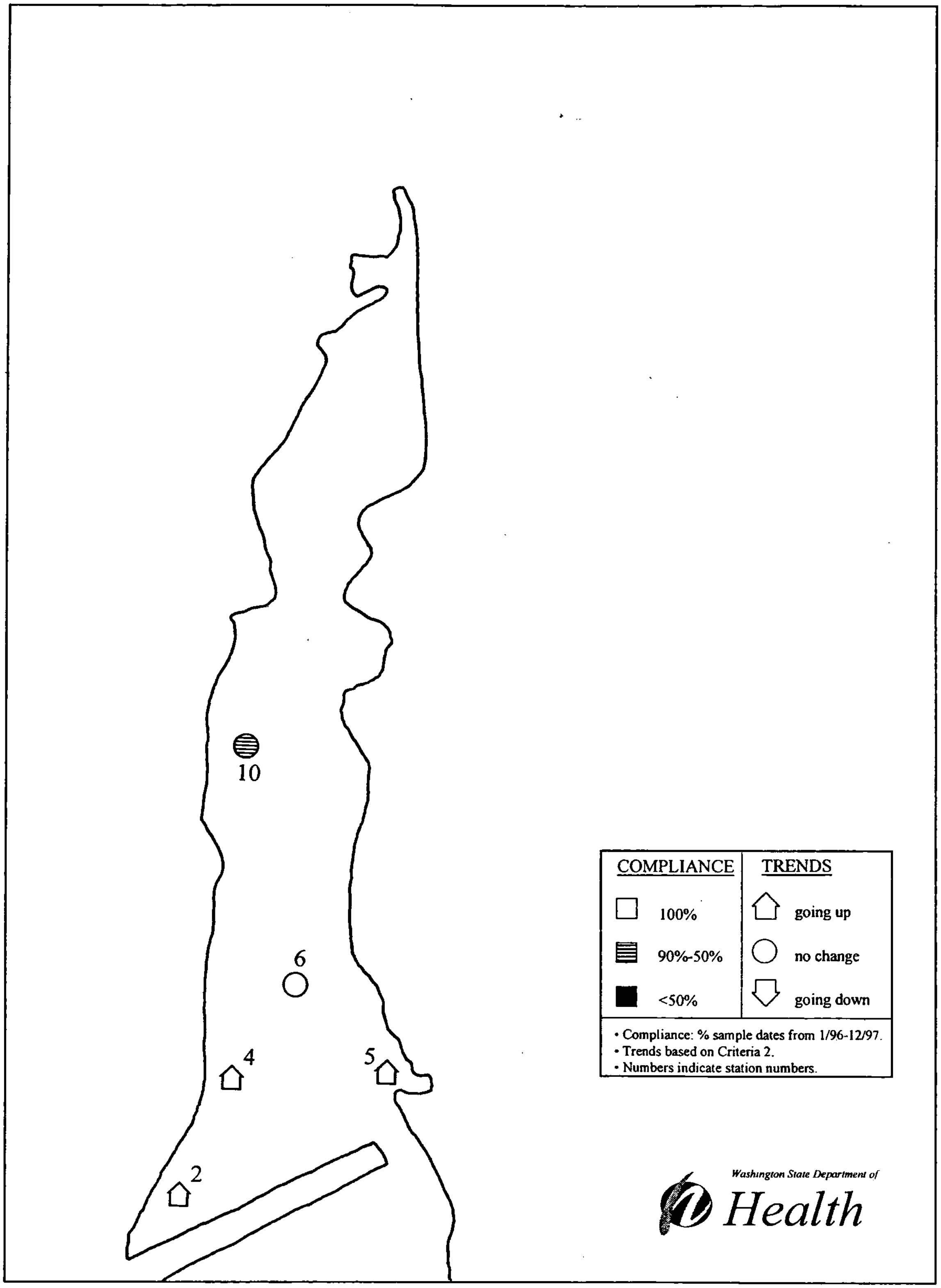

Figure 6. Fecal coliform trends and status in Burley Lagoon

Samish Bay

Samish Bay watershed in north Puget Sound differs somewhat from its three south Puget Sound counterparts (Henderson Inlet, Oakland Bay and Burley Lagoon). The Samish watershed is much larger. Farms are larger commercial operations. Pastures on the broad delta are diked from the Samish River and Bay. Pasture runoff is discharged through tide gates and pumps, rather than over land or through uncontrolled ditches. The pastures provide seasonal refuge for several species of migrating birds. Homes tend to be clustered into discreet small communities, rather than scattered over numerous small lots. Intensive residential development has been confined to the upper watershed.

In 1994 several growing areas in Samish Bay were downgraded from "Approved" to either "Restricted" or "Prohibited" (DOH 1996). The primary sources of contamination were failed on-site systems in Blanchard and discharge of raw sewage into Edison Slough from the Edison sewer system. Many failed on-site systems in Blanchard have been repaired. A new collection and treatment system with a ground discharge has just been completed in Edison. Remedial action has been driven primarily by citizen action in the two bayside communities.

Figure 7 summarizes status and trends in Samish Bay. Station 13 (near Edison Slough) failed the growing area standard on all sampling dates during the most recent two years. All other sites complied. Seven sites showed increasing trend in Criterion 2 (90th percentiles). These stations included Station 13, Station 10 in mid-bay, and stations 1–4 along the outer boundary of the sampling grid. Six sites showed decreasing trend, including three located in the northeast corner near Blanchard (Stations 6, 7, 8).

The improvement in the northeast end of Samish Bay may have been brought about by the repair of failed on-site sewage systems in Blanchard. Conditions at Station 13 have been stable recently. Criteria at this site should drop because discharge of raw sewage into Edison Slough has recently stopped.

The effect of agricultural discharge through the tide gates and pumps has not yet been thoroughly evaluated. However, conditions at sampling stations located closest to agricultural discharge points (Station 9 at mid-bay; and Stations 11 and 12 in the Southwest corner near Samish River) do not suggest major agricultural impact.

East Sound, Penn Cove, Sequim Bay, Quilcene Bay, and Port Blakely

Penn Cove and Sequim Bay are classified "Conditionally Approved." Penn Cove has been sampled since 1988. Sequim Bay has been sampled monthly since 1992. Most of Quilcene Bay, East Sound, and Port Blakely are classified "Approved," and have been sampled since 1992. Data from each of the five growing areas for all dates sampled were pooled and criteria calculated (Table 1).

Table 1. Growing area criteria in five PSAMP shellfish harvest areas.

PSAMP Area	Criterion 1 (geometric means)	Criterion 2 (ninetieth percentiles)
Sequim Bay	2.3	4.5
Penn Cove	2.5	6.5
Quilcene Bay	3.6	12.4
East Sound	3.2	9.1
Port Blakely	3.0	4.2

Table 1 suggests that fecal coliform levels in the five growing areas were generally very low. Both criteria were much lower than their respective maximum allowable limits. Each of the five growing areas has met the growing area standard. Trends were not calculated because, considering the low levels overall, trends would likely be meaningless.

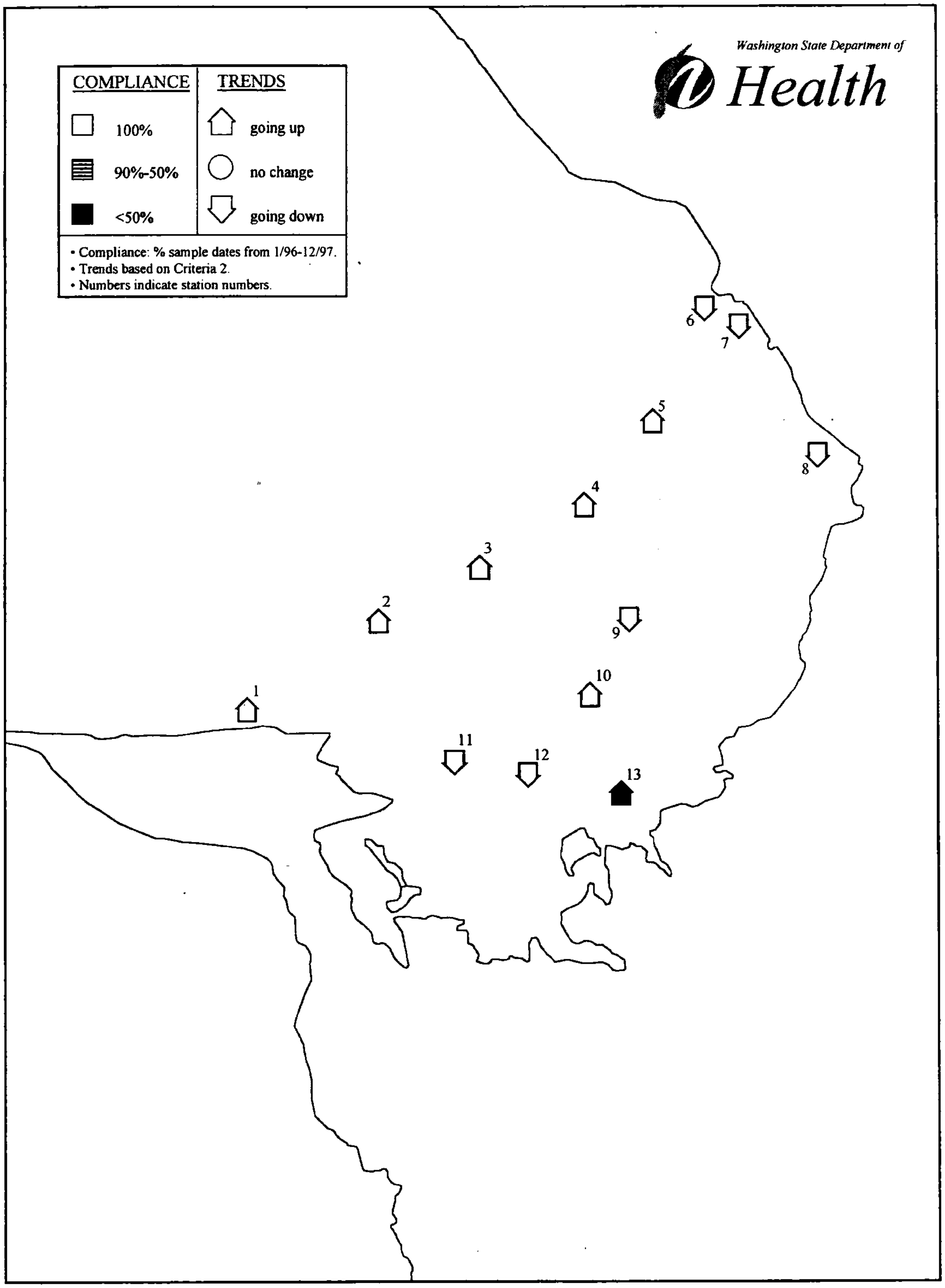

Figure 7. Fecal coliform trends and status for Samish Bay

Conclusions

Out of a total of 108 sampling sites in nine PSAMP growing areas, 103 sites met the growing area standard on all sampling dates during the last two years: Five sites failed to meet the standard on some dates. One site in each of Henderson Inlet and Samish Bay failed to comply on any date. The results suggest that serious fecal pollution tends to be highly localized. On the other hand, fecal coliform levels elsewhere in PSAMP areas are generally low in most places at most times. Trends in fecal coliform bacteria were determined in four PSAMP growing areas. Upward trends in criteria in Henderson Inlet and Burley Lagoon indicate the need to redouble the effort to locate and repair nonpoint sources of fecal pollution. Decreasing trends in criteria in Oakland Bay and parts of Samish bays are likely due to remedial action.

Fecal loading from urbanizing watersheds in Puget Sound will continue to threaten shellfish resources. The threat is exacerbated by potential failure of both existing treatment systems and new ones installed by increasing numbers of incoming residents. Nonpoint treatment systems must be perpetually monitored and maintained. This task must ultimately be borne by the rural homeowner. Government should fund programs to monitor rural treatment systems, educate and assist homeowners in their operation and maintenance, and assure their repair or replacement in case of failure.

Acknowledgements

The author acknowledges the suggestions and critique of management and staff of the Office of Shellfish Programs, Washington Department of Health. The author also acknowledges the largely unsung efforts of sanitarians and conservation technicians in their one-on-one work with rural residents. The role of the many citizens who have made significant economic sacrifices to repair their systems in order to improve water quality is also recognized.

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Bioaccumulation of Chemical Contaminants in Transplanted and Wild Mussels in the Duwamish River Estuary, Puget Sound, Washington

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Introduction

This paper presents some of the results of a year-long monitoring program aimed at better understanding chemical contamination in the Duwamish River estuary, part of the highly urbanized Green/Duwamish River watershed in western Washington. Chemicals enter the lower watershed both from point sources—such as permitted industrial discharges, treatment plants, storm water, combined sewer overflows (CSOs), and accidental spills and leaks—and from nonpoint sources—including runoff, atmospheric deposition, and ground water. Of particular interest in this study are the chemical contributions of CSOs relative to other sources of pollution entering the Duwamish River estuary.

These studies were conducted in September 1996 (dry season) and in March 1997 (wet season) employing both transplanted and wild mussels. Analysis of the concentration of chemicals in the soft tissues of mussels was the basis of chemical monitoring. It is well established that tissue contamination in mussels and other bivalves increases or decreases as environmental contamination increases or decreases (NOAA, 1989). It is for this reason that mussels are particularly good sentinels of contamination.

The key questions addressed by this research included: 1) Are chemicals entering the Duwamish River estuary bioavailable and bioaccumulated? 2) Do concentrations of bioavailable chemicals change seasonally? 3) Are the contributions of chemicals from CSOs measurable in a biological receptor, e.g., mussels? While mussel tissue was analyzed for a wide variety of metals and semivolatile (extractable) organic compounds, only the results of analyses for copper, tributyltin (TBT), polychlorinated biphenyls (PCBs), and lipids are reported in this communication.

Methodology

Mussel Deployment and Retrieval

Juvenile mussels, *Mytilus galloprovincialis*, were collected from the Taylor United Inc. mussel farm on Totten Inlet, Washington. Following the general recommendations of Salazar and Salazar (1995), 50 mussels 25–40 millimeters (mm) in size were loaded into individually compartmentalized mesh bags using plastic cable ties. Plastic oyster cultch netting (15-mm mesh stretch) was used for this purpose. Prior to being loaded into mussel bags, all mussels were weighed to the nearest 0.001 gram (g). Statistical analyses (see methodology described below) determined that mussel lengths and weights in all groups were the same ($P<0.05$) at the time of deployment.

The mussels were deployed at each site by boat. Ten mesh bags containing 50 mussels each were suspended from a float anchored at each study site. Five mesh bags were suspended 1 meter (m) below mean lower low water (MLLW); five mesh bags were suspended 3 m below MLLW but at least 1 m above the bottom. The mesh bags were deployed for four weeks both in September 1996 (dry season) and in March 1997 (wet season).

Wild mussels, *Mytilus trossulus*, were collected coincident with retrieval of transplanted mussels. Wild mussels were collected randomly from concrete pilings 1 m above MLLW at some of the mussel

transplant locations. Fifty mussels 25 to 40 mm in size comprised each wild mussel sample. No less than triplicate samples were collected at each location, each sample coming from a different piling.

Sampling Locations

Transplanted mussels were deployed in the Duwamish Waterway at the Brandon Street CSO, at the Duwamish/Diagonal Way CSO/storm drain, at the Chelan Street CSO, and at two in-river reference sites (Figure 1). Separated storm water is also discharged through the Duwamish/Diagonal CSO outfall. Additionally, transplanted mussels were deployed in Elliott Bay at the Denny Way CSO and at a marine reference site (Taylor United, Inc. mussel farm on Totten Inlet). The mussel transplants from the Denny Way and Chelan Street CSOs were lost possibly due to vandalism or storm activity.

The first in-river reference site (Slip #1) was located approximately 500 m below the Brandon Street CSO on the east (same) side of the river. The second in-river reference site was located at the farthest downstream point of Kellogg Island and is approximately 300 m west of the Duwamish/Diagonal CSO/storm drain. Sediments at these sites were either previously sampled as part of the Elliott Bay Action Program (PSEP, 1988) or by King County, and were found not to violate Washington State Sediment Management Standards (Chapter 173-204-WAC) for either metals or organics (R. Shuman, King County Water and Land Resources Division, Seattle, Washington, personal communication).

Wild mussels were collected in the Duwamish Waterway from Slip #4, Brandon Street CSO, Duwamish/Diagonal Way CSO/storm drain, Terminal 105, Hanford Avenue CSO, and in Elliott Bay at the Elliott Bay Pier (Figure 1).

At each CSO location, the mussel transplants were deployed immediately in front of or just below (downriver) the discharge pipe. Distance from the outfall to the mussel transplants was 25 m or less. At these same locations, wild mussels were collected as close to the outfall as practical. Wild mussels were collected approximately 25 m below the Brandon Street CSO outfall, approximately 50 m above the Duwamish/Diagonal CSO/storm drain outfall, and approximately 50 m below the Hanford CSO outfall. The Duwamish/Diagonal Way CSO/storm drain wild mussel collection site is affected by the discharge plume on the incoming tide; that is, the discharge plume bends upriver on the incoming tide.

Salinity and Other Water Quality Parameters

Salinity, temperature, dissolved oxygen, and pH were measured twice at each transplant station during the dry season deployment and once during the wet season deployment. Additionally, these parameters were measured weekly at a subset of the transplant locations (Brandon Street CSO, Chelan Street CSO) and elsewhere (Hanford Avenue CSO) over the greater wet season (December 1996 to June 1997). The latter data are not presented in this paper.

Laboratory Processing

After retrieval, the mussels were shucked and the available tissue composited for chemical analyses. Approximately 110 g of tissue was pooled from the 50 mussels from each bag to represent a single sample. Using clean gloves, dissections were conducted with teflon knives on the frozen tissue tp prevent fluid loss internal to the shell. Tissues were homogenized in a blender fitted with titanium blades. Puget Sound Estuary Program methodology (PSEP, 1996a) was followed for the storage of tissues until chemical analysis.

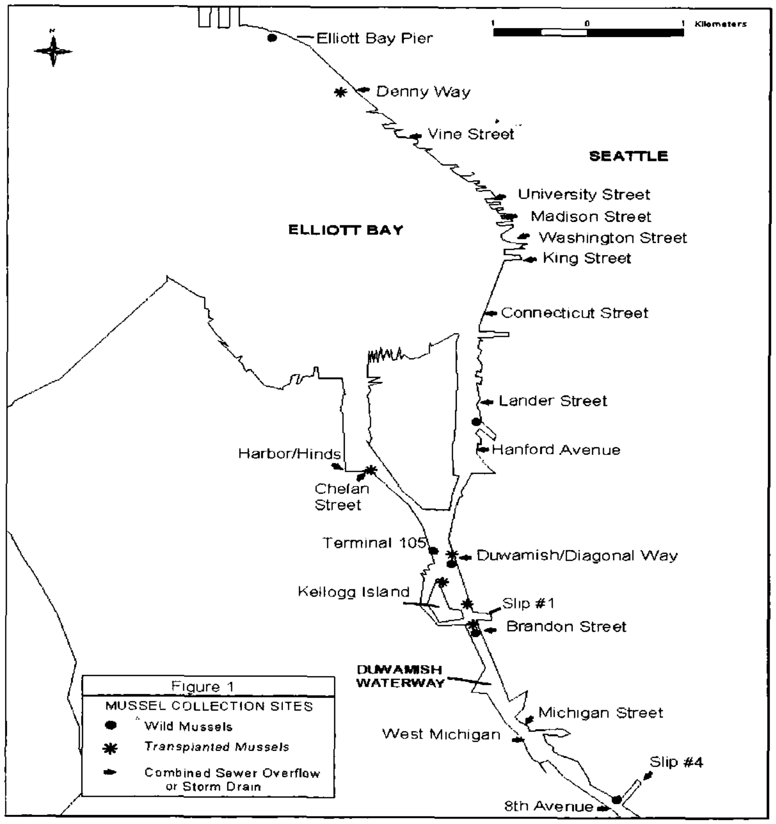

Figure 1. Collection sites for wild mussels in the Duwamish Waterway and Elliott Bay.

Chemical Analytical Procedures

Tissue digests, extractions, and other analytical procedures also followed the Puget Sound Estuary Program methodology (PSEP, 1996b, 1996c). Copper was analyzed by ICPMS (inductively coupled plasma mass spectrometry) following U.S. Environmental Protection Agency (USEPA) Method 6020. PCB analyses were performed following USEPA Method 8082 (SW-846) using GC dual-ECD (gas chromatography dual-electron capture detector) techniques. Tributyltin (TBT) was analyzed by GCFPD (gas chromatography flame photometric detection) following the methods of Unger et al. (1986). Percent lipids were determined gravimetrically.

Statistical Analysis

Non-parametric methods were used at the first level of statistical analysis. For analysis that involved comparison of mussel groups from two locations or depths, the Kolomogorov-Smirnov Statistic was applied (Conover, 1980). For multiple comparisons, the Mann-Whitney Statistic (Winkler and Hayes, 1975) was used. If significant differences were found, an analysis of variance (ANOVA) followed by Bonferroni's Modified Least Significant Difference Test (Timm, 1975) were used to identify specific differences.

Results

Concentrations (medians and interquartile ranges) of the three chemicals and percent lipids in composite samples of transplanted and wild mussels from the Duwamish River estuary are presented in Table 1.

Table 1. Chemical concentrations in composites of 60 mussels.

	[redacted]											
	Median	IQR [a]	N	Median	IQR	N	Median	IQR	N	Median	IQR	N
DRY SEASON												
[redacted]												
Brandon Street-1	1.18	0.04	5	47.3	5.9	5	56.4	5.4	4	0.99	0.51	5
Slip #1-1 (Ref)	1.22	0.11	5	35.6	14.6	5	65	6.7	5	1.2	0.1	5
Duwamish/Diagonal-1	1.14	0.25	5	49	12.7	5	60.6	9.8	4	1.1	0.1	5
Duwamish/Diagonal-3	1.48	0.01	2	42.8	6.7	2	54.8	0.75	2	0.95	0.01	2
[redacted]												
Brandon Street	0.97	0.26	3	37.8	7.8	5	43.3	5.4	3	0.53	0.4	3
Duwamish/Diagonal	1.01	0.04	5	70.3	25.1	5	52.3	10.2	5	0.68	0.42	5
Terminal 105	1.14	0.08	3	59.5	8.1	3	31.2	1.1	3	0.77	0.06	3
Hanford Avenue	1.53	0.17	3	164	41.5	5	28.7	2.1	3	0.73	0.09	3
[redacted]	0.86	0.07	7	3.3	0.4	7	<MDL[b](13)	--	7	2.2	0.35	7
WET SEASON												
[redacted]												
Brandon Street-1	0.58	0.1	3	15.5	2.1	2	<MDL (13)	--	3	0.61	0.25	3
Brandon Street-3	0.87	0.1	3	27.6	6.2	3	<MDL (13)	--	3	1.4	0.38	3
Kellogg Island-1 (Ref)	0.85	0.01	2	9.3	--	1	<MDL (13)	--	2	1.3	--	1
Kellogg Island-3 (Ref)	0.99	0.23	5	18.3	3.7	4	<MDL (13)	--	5	1.74	0.34	3
Duwamish/Diagonal-1	1.07	0.7	4	11.6	1.8	4	<MDL (13)	--	4	1.5	0.82	4
Duwamish/Diagonal-3	1.69	0.43	3	27.5	5.6	3	<MDL (13)	--	3	2.32	0.3	3
[redacted]												
Slip #4	1.18	0.06	3	21.8	1.1	3	53.6	12.3	3	1.05	0.32	3
Brandon Street	1.69	0.11	3	31.3	6.7	3	27.7	1.4	3	1.2	0.25	3
Duwamish/Diagonal	1.31	0.18	3	18.5	5.2	3	<MDL (13)	--	3	0.64	0.21	3
Terminal 105	1.04	0.07	3	19.9	4.2	3	<MDL (13)	--	3	0.46	0.12	3
Hanford Avenue	2.15	0.03	3	72.8	4.7	3	<MDL (13)	--	3	1.07	0.06	3
Myrtle Edwards Park	1.1	0.03	3	58.2	0.5	3	<MDL (13)	--	3	2.3	1.3	3
[redacted]	0.48	0.07	6	3.2	2.5	6	<MDL (13)	--	6	2.7	0.53	6

[a]Interquartile range
[b]Method detection limit

Copper

Copper concentrations in transplanted mussels ranged from 0.58 to 1.69 milligrams/kilogram (mg/kg) wet weight. The highest concentrations were found near the Duwamish/Diagonal Way CSO/storm drain both during the dry season and the wet season. The concentrations in Duwamish/Diagonal Way CSO/storm drain mussels were significantly greater than the concentrations in mussels from other transplant locations ($P<0.05$). The lowest concentrations of copper were found in mussels deployed at the marine reference site. Concentrations of copper were generally lower in transplants deployed during the wet season when compared to transplants deployed during the dry season ($P<0.05$). Also, at the Brandon Street CSO in the wet season, concentrations of copper were higher in mussels deployed near the bottom than mussels deployed near the surface ($P<0.05$).

Copper concentrations in wild mussels ranged between 0.97 and 2.15 mg/kg wet weight. Highest

concentrations in wild mussels occurred near the Hanford Avenue CSO sampling site, both during the dry (1.53 mg/kg wet weight) and wet seasons (2.15 mg/kg wet weight). Metals from both a shipyard and an abandoned lead smelter may influence this site. The concentration of copper accumulated at this site is higher than the concentrations of copper accumulated at all other wild mussel collection sites ($P<0.05$). Contrary to what we observed in transplanted mussels, the concentrations of copper found in wild mussels were generally higher during the wet season. This was true at all CSO sampling sites (Brandon Street, Duwamish/Diagonal Way, and Hanford Avenue). These differences are statistically significant at the $P<0.05$ level. The exceptions were Terminal 105 and the marine reference site, which had higher concentrations in the dry season.

We also compared copper concentrations in transplanted mussels with concentrations of copper in wild mussels at the same locations to evaluate the rate of uptake by transplanted mussels over their one-month exposure. We learned that in the dry season the copper concentrations in transplanted mussels from the Brandon Street CSO and Duwamish/Diagonal CSO/storm drain were essentially the same as the concentrations of copper in the wild mussels from these locations. These data suggest that uptake of copper was rapid, reaching equilibrium in one month. The copper concentrations in transplanted mussels in the wet season, however, did not always reach the levels of copper concentrations in the wild mussels. This was true at Brandon Street and also at Kellogg Island. The Kellogg Island transplants were compared to the Terminal 105 wild mussels.

TBT

In the dry season, concentrations of TBT in transplanted mussels ranged between 3.3 micrograms/kilogram (µg/kg) wet weight and 49.0 µg/kg wet weight. The lowest concentrations occurred at the marine reference site, the highest concentrations at Duwamish/Diagonal Way CSO/storm drain. There were no significant differences among in-river transplant locations ($P<0.05$). During the wet season, concentrations of TBT in transplanted mussels were significantly lower ($P<0.05$) ranging between 3.2 and 27.6 µg/kg wet weight. During the wet season, differences in concentration were also apparent with depth. Concentrations of TBT at the Brandon Street CSO were significantly greater ($P<0.1$) in mussels maintained at the –3m MLLW level when compared with mussels maintained at –1m MLLW. At the Duwamish/Diagonal CSO/storm drain, concentrations of TBT in mussels maintained at the –3 m MLLW level were also greater ($P<0.05$) than the concentrations of TBT in mussels from the –1 m MLLW level.

In the dry season, concentrations of TBT in wild mussels were higher at the Duwamish/Diagonal Way CSO/storm drain than at the Brandon Street CSO. They were higher yet at Terminal 105 and highest near the Hanford Avenue CSO. These differences are significant at the $P<0.05$ level. While this gradient is less clear in the wet season, the highest concentrations of TBT were again encountered below the Hanford Avenue CSO. Concentrations of TBT in wild mussels were also significantly lower in the wet season than in the dry season ($P<0.01$). Concentrations in wild mussels from Elliott Bay Pier were less than the concentrations in wild mussels from Duwamish/Diagonal CSO/storm drain but greater than the concentrations in wild mussels from the Hanford Avenue CSO sampling site.

Where data are available for both transplanted and wild mussels at the same site (Brandon Street and Duwamish/Diagonal CSO/storm drain), no statistically significant ($P<0.05$) differences were apparent in concentrations of TBT between transplanted and wild mussels. These data suggest that TBT was rapidly accumulated to an equilibrium level.

PCBs

While PCBs were not detected in transplanted mussels maintained at the marine reference Site, they were detected in all transplants in the Duwamish Waterway in the dry season. Concentrations ranged between 54.8 µg/kg wet weight and 65.0 µg/kg wet weight. PCB concentrations in wild mussels in the dry season generally appeared to be lower than PCB concentrations in transplanted mussels in the dry

season, if compared on a wet weight basis. If normalized to percent lipid (data not shown), however, the concentrations of PCBs among all locations (transplant and wild) in the dry season were not statistically different (P<0.05), suggesting that accumulation in transplanted mussels occurred rapidly, reaching equilibrium over the four-week deployment. PCBs were only found in wild mussels in the wet season at Slip #4 (53.6 µg/kg wet weight) and at Brandon Street CSO (27.7 µg/kg wet weight).

Lipids

Lipid content was generally highest in transplanted mussels maintained at the marine reference site. Values were 2.20% in the dry season and 2.70% in wet season. For transplants deployed in the Duwamish Waterway in the dry season, lipid content varied between 0.99% and 1.20%. Lipid content in transplants tended to be higher in the wet season, ranging between 0.61% and 2.30%. Lipid content also tended to vary with depth. Mussels maintained at –3 m at the Duwamish/Diagonal CSO/storm drain in the wet season contained more lipid than mussels maintained at –1 m (P<0.05). Although not shown in Table 1, lipid contents of mussels deployed at the marine reference site did not change from their pre-deployment levels, both in the dry and in the wet seasons.

Wild mussel lipid content in the dry season varied over the range of 0.53% to 0.77%. The range in the wet season was generally higher, 0.46% to 2.32%. The difference is statistically significant (P<0.05) for most locations where comparative data were available. The highest value (2.32%) was found in mussels from the Elliott Bay Pier in the wet season.

Salinity Regime and Other Water Quality Parameters

Salinity varies with tidal stage and runoff. During the dry season in the Duwamish Waterway, salinity tends to be greater. For example, at the ebb for the first low tide of the day at Brandon Street CSO on October 8, 1996, salinity was 22.6 parts per thousand (ppt) at –1m MLLW and 27.1 ppt at the –3m MLLW level. The river flow on this date was 238 cubic feet per second (cfs). The temperature, dissolved oxygen, and pH at the –1 m MLLW level were 13.0 _C, 6.1 parts per million (ppm), and 7.0, respectively. At the –3 m MLLW level , these parameters were 12.6 _C, 5.7 ppm, and 7.12, respectively. During the wet season, salinity in the Duwamish Waterway decreases significantly as runoff and river flows increase. On March 26, 1997, at the ebb of the first low tide of the day at Brandon Street CSO, salinity at –1m MLLW was only 3.0 ppt. Salinity at –3m MLLW was 8.0 ppt. River flow was 3,080 cfs. The temperature, dissolved oxygen, and pH at –1 m MLLW were 8.7 _C, 10.5 ppm, and 7.2, respectively. These parameters were not greatly different at –3 m MLLW.

Discussion

Historical Data

Several previous studies report historical levels of copper, PCBs, and TBT in mussels from the Duwamish River estuary. Copper concentrations in mussels from Four-Mile Rock (Elliott Bay) in 1986, 1987, and 1988, were 12, 8.7, and 11 µg/g dry weight, respectively (NOAA, 1989). These convert from dry weight to wet weight (assuming 87% moisture content [Johnson and Davis, 1996]) to 1.56, 1.13, and 1.43 mg/kg wet weight, respectively. These concentrations agree well with the values (0.97–1.53 mg/kg wet weight) reported here.

NOAA (1989) also analyzed the mussels from Elliott Bay for total PCBs and found concentrations of 1110, 580, and 450 µg/kg dry weight for 1986, 1987, and 1988, respectively. Converting from dry weight to wet weight, these concentrations become 143, 75, and 58 µg/kg wet weight. NOAA's 1988 total PCB concentration is relatively close to concentrations (54.6–65.0 µg/kg wet weight) observed in the present study. Johnson and Davis (1996) found 44 µg/kg wet weight of PCBs in mussels from the lower Duwamish Waterway, which also provides excellent agreement with the level (28.7 µg/kg wet

weight) found in the lower Duwamish Waterway (Hanford Avenue CSO) in this study.

The TBT data in mussels from the Duwamish Waterway presented in Table 1 are the first such data from the waterway to be published. These data indicate that highest levels occurred in the lower waterway where shipping and ship repair activities are concentrated. Short and Sharp (1989) included three locations in Elliott Bay in their 1986 and 1987 surveys. They found concentrations ranging from 50 to 230 µg/kg wet weight, which are not greatly different from the range of values (35.6 and 164.0 µg/kg wet weight) reported in the dry season in this study.

While numerous measurements of lipid content for mussels have been published, perhaps the most germane to the present study are the results of Johnson and Davis (1996). They determined that wild mussels from the Duwamish Waterway contained 1.1% lipid, which is in the range of values for wild mussels (0.53%–2.3%) reported in this study.

Dynamics of Chemical Exposure

We have interpreted our results to mean that exposure in the Duwamish Waterway changes seasonally. Based on the transplanted mussel data, exposure to copper, TBT and PCBs tended to decrease during the wet season throughout the study area. Based on wild mussel data, however, exposure to copper may have increased in the wet season at some locations.

The findings that copper, TBT, and PCBs in transplanted mussels decreased in the wet season first suggested an alternative explanation. Knowing that both transplanted and wild mussel types were exposed to lower temperatures and very low salinities during the wet season, we first thought that the mussels had stopped pumping/feeding and that they had lived off their lipid reserves over this period. They then might not be expected to accumulate as much chemical. This may not be the case because lipid levels remained quite high in the transplanted mussels throughout the wet season deployment. Actually, lipid levels for both transplanted and wild mussels were generally higher during the wet season when compared with the dry season. Also, more copper was accumulated by the wild mussels near CSOs during the wet season suggesting that the mussels continued to pump and feed normally.

Sources of Bioaccumulatable Copper, TBT, and PCBs in the Duwamish Estuary

At all CSO locations, the concentrations of copper were found to increase in wild mussels in the wet season. This increase in tissue concentration was 29.7%, 40.5%, and 74.2% at the Brandon Street CSO, Duwamish/Diagonal CSO/storm drain, and Hanford Avenue CSO, respectively. One possible source of this copper is the CSOs/storm drains. Copper (mean of 43.6 µg/L) is known to occur in the stormwater component of CSOs (e.g., Hinds CSO) discharging to the Duwamish Waterway and has been found at 41.1–119.0 mg/kg dry weight in the sediments from the Duwamish/Diagonal storm drain (King County, 1997a). Copper commonly occurs in CSOs discharging elsewhere to Puget Sound, e.g., City of Bremerton (Fohn 1997). While the data are not presented in this paper, the concentrations of cadmium, lead, and zinc also increased in wild mussels collected near the Brandon Street CSO, Duwamish/Diagonal CSO/storm drain, and Hanford Avenue CSO in the wet season.

Another possible source of the bioavailable copper found in wild mussels near the CSOs is the sediments. It is conceivable that copper deposited to the sediments from past overflows could have been resuspended during recent (winter 1996–1997) overflows, although we might have expected other chemicals, e.g., PCBs, to be resuspended and accumulated in wild mussels at higher concentrations in the wet season, which was not the case. Both the Brandon Street and Duwamish/Diagonal CSOs discharge directly to the intertdial zone and have the potential to scour chemicals from the surface sediments. Copper concentrations in the sediments at the Brandon Street CSO range between 61.0–72.4 mg/kg dry weight. They range between 62.9 and 108 mg/kg dry weight in the sediments near the Duwamish/Diagonal CSO and storm drain.

Ground water is another possible source of the increased copper accumulation in the wild mussels.

Ground water collected from wells on the Chiyoda/Chevron property, which is just upriver from the Duwamish/Diagonal Way outfall contained a maximum of 200 µg/l copper (King County 1997). There are no comparable analyses of groundwater sources near the Brandon Street or Hanford Avenue CSOs.

The fact that the increase in copper in wild mussels cannot be explained by normal seasonal differences in copper concentrations in the Duwamish Waterway is supported by the finding that we did not find an increase in copper in wild mussels from the Terminal 105 site. The Terminal 105 site is on the opposite (east) side of the river from where most CSOs and storm drains discharge.

The fact that the transplanted mussels were not exposed to the same number of overflows and storm drain discharges as the wild mussels might explain why the transplanted mussels failed to demonstrate a commensurate increase in copper concentrations at the three CSO locations. The transplanted mussels were only exposed to six overflows at Brandon over the one-month deployment period, and only one overflow at the Duwamish/Diagonal Way CSO/storm drain over this period. The wild mussels were exposed to many more overflows since the beginning of the wet season in October 1996.

Additional work is underway to address the source of copper and other metals found to increase in some wild mussel tissues during the wet season. A hydrodynamic and chemical fate mathematical model presently being developed by King County may be particularly helpful in this regard (King County, 1997b).

We also believe that the findings of less TBT and almost no PCBs in both transplanted and wild mussels in the wet season reflect different sources of these chemicals in the estuary. Because the source of PCBs in the Duwamish Waterway is the sediments, we might not expect mussels to bioaccumulate much PCB if the overlying and less-dense lens of fresh water occurring in the wet season acts as a barrier to the complete mixing of PCBs into the water column from the sediments.

While TBT also partitions to the water column from the sediments and would be subjected to the same hydrodynamic processes as PCBs, TBT is also known to elute into the water column from the hull paints/coatings of ships at moorage in the Duwamish Waterway and Elliott Bay. This is a direct input of TBT to the overlying lens of fresh water entering the waterway, which could account for more TBT becoming available for bioaccumulation. While less TBT was found in mussels in the wet season, there was not the near-total exclusion observed for PCBs. Also, more TBT in the mussel transplants maintained at the –3-m depth in the wet season tends to support this interpretation.

Conclusions

1) Bioaccumulation varied with both location in the estuary and with depth. Concentrations of copper and TBT in wild mussels were highest in the lower Duwamish Waterway while concentrations of PCBs tended to be more uniform over the study area. In the wet season, mussel transplants indicated that concentrations of copper and TBT were greater at –3 m than at –1 m MLLW.

2) Bioaccumulation also varied seasonally in the Duwamish Waterway. Concentrations of all three chemicals were lower in mussel transplants in the wet season. This may be due to freshwater runoff. This was particularly true for TBT and PCBs whose sources may not be dependent on wet weather events. Wet season levels of copper in wild mussels were higher at some locations. Additional work is underway to determine the source of increased levels of copper and other metals found in some wild mussels in the wet season.

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Trace Metals in Edible Clams from King County Beaches

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Introduction

Bivalves are frequently used as indicator organisms for environmental measurements in aquatic environments as they tend to accumulate pollutants in their tissues, a process known as bioaccumulation. The amount of pollutants bioaccumulated is a concern as bivalves may be consumed by humans and wildlife. King County has monitored organic compounds, trace metals, and bacteria in bivalve tissues at designated King County beaches for the past several years.

The primary objective of King County's shellfish monitoring program from 1993 to 1996 was to comply with the County's National Pollutant Discharge Elimination System (NPDES) permits for the East Division Reclamation (Renton), West Point, and Alki Sewage Treatment Plants and the Carkeek Combined Sewer Overflow Treatment Plant. The East Reclamation and West Point Treatment Plants discharge secondary treated effluent into the central basin of Puget Sound, whereas the Alki plant discharges sanitary sewer/stormwater primary treated effluent into the central basin. Sample sites were chosen based upon their proximity to treatment plant discharges. Edible bivalves (clams) were chosen as a biomonitor as they are easily obtained and are the main group of organisms recreationally harvested from King County beaches. The primary goal of the monitoring data was to assess pollutant body burdens in edible clams, which may be transferred to both the humans and wildlife that consume them. A secondary goal was to compare the data with results obtained from other studies.

The sampling protocols were designed in order to achieve the primary data goal, which was to assess pollutants bioaccumulated in clams being recreationally harvested. All edible clams collected of sufficient size were composited into a single sample for each site. Thus, the species assemblage differed from beach to beach and from year to year, depending on which edible species were readily available. While this data is useful for determining pollutant burdens to recreational harvesters consuming available clams, it does present limitations. Spatial and temporal comparisons are not possible, because the clam species contained in each sample differed and it has been shown that bioaccumulation rates can differ by species (Phillips & Rainbow, 1993; Faigenblum, 1988).

In this paper, four years of data are presented and discussed for nine trace metals measured in clam tissues collected from eight sites.

Methods

Field Methods

Clams were collected from the following eight beaches in 1993, 1994, 1995, and 1996: Carkeek Park (KSHZ03), Blue Ridge (KSJX02), Golden Gardens (KSLU03), West Point-north of lighthouse (KSSN04), West Point-south of lighthouse (KSSN05), Magnolia (KSUR01), and Alki Point (LSKR01 and LSKS01) (Figure 1). In 1993, clams were collected in September and from 1994 to 1996 they were collected in July. Species composition varied at each beach and species collected (in order of preference) included native littleneck (*Protothaca staminea*), manila (*Venerupis japonica*), butter (*Saxidomus giganteus*), cockle (*Clinocardium nuttalli*), and horse (*Tresus capax*) clams. Only clams of edible size were retained. After digging with a shovel or trowel, clams were sealed in glass jars (plastic bags in the case of large horse clams) and held in ice chests. Clams with chipped or cracked shells were rejected.

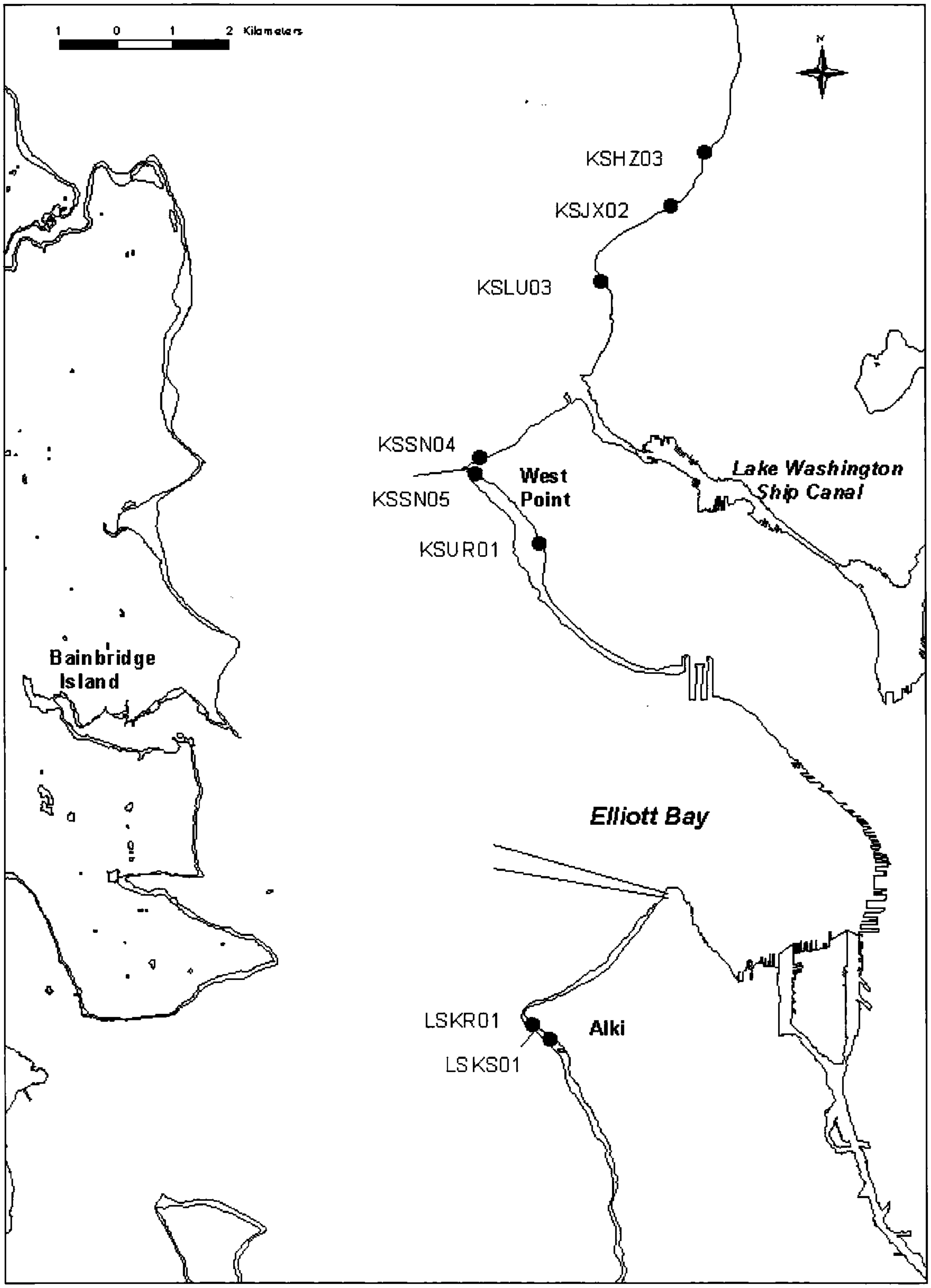

Figure 1. Sample locations.

Laboratory Methods

All clams were shucked and whole tissues were mixed to form a single composite sample in accordance with Puget Sound Estuary Program (PSEP) recommended protocols (PSEP, 1996a). A minimum of 350 grams of tissue was obtained for each site.. The tissues were stored frozen in pre-cleaned jars for later analysis.

All metals, with the exception of mercury, were digested using a nitric acid/hydrochloric acid/hydrogen peroxide digestion and then analyzed by inductively coupled plasma emission spectroscopy (ICP). Mercury was analyzed by cold-vapor atomic absorption spectrophotometry following digestion by the nitric acid/sulfuric acid method (PSEP, 1996b). Quality assurance/quality control procedures included the use of blanks, duplicates, and spikes.

Results

Tissue samples were analyzed for 16 metals. However, only arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver, and zinc are discussed in this paper. Results are reported in mg/kg (ppm) on a wet weight basis and are presented in Table 1.

Arsenic

Between 1993 and 1996, concentrations ranged from 1.0 and 3.4 mg/kg at all beaches. Except for KSSN04, most values were below the laboratory's reported detection limit (RDL) but above the method detection limit (MDL). The maximum concentration (3.4 mg/kg) was detected at stations KSSN04 and KSUR01. Arsenic concentrations detected in clams from King County beaches are similar to concentrations detected in edible shellfish from other studies in Puget Sound (WDOH, 1996; Cubbage, 1991; Faigenblum, 1988).

Cadmium

Cadmium concentrations ranged from below the MDL (0.06) to 0.27 mg/kg. As with arsenic, most values were below the RDL but above the MDL. The highest concentrations were found at station KSHZ03, which had a mean concentration from 1993 to 1996 of 0.21 mg/kg (n = 4).

Chromium

Chromium was detected in all samples collected and ranged from 0.19 to 1.13 mg/kg, with one exception discussed below. Values were above the RDL with the exception of three samples. The results obtained from this study are similar to those from other Puget Sound studies (WDOH, 1996). The value for station KSJX02 in 1994 was 31.30 mg/kg, which was over 26 times higher than the next highest value. The sample consisted of bent-nosed clams, *Macoma nasuta*, which is not a target species because this clam has a different feeding strategy (surface deposit feeder) from the preferred species (filter feeder). It has been shown that *Macoma spp.* bioaccumulate copper and zinc more than other clam species and as this data suggests, chromium as well (Faigenblum, 1988). Therefore, this value will not be included in further discussions.

Copper

Copper was detected in all samples above the RDL. Concentrations ranged from 0.89 to 5.10 mg/kg with the lowest concentration found at station KSHZ03 and the highest at KSUR01. The values obtained from 1993 to 1996 monitoring are similar to results obtained from a previous study (WDOH, 1996).

Lead

All detected values were below the RDL (0.4 to 1.0 mg/kg) and most values were below the MDL (0.3 mg/kg). With the exception of the 1.0 mg/kg value (obtained for the bent-nosed clam sample), all

other detected values were very close to the MDL. Lead results are similar to values obtained for other studies (WDOH, 1996; Faigenblum, 1988).

Mercury

Mercury was detected in all but two samples, but at concentrations below the RDL. Concentrations ranged from 0.004 to 0.014 mg/kg. The highest concentrations were found at stations KSSN04 and KSUR01, which had mean concentrations from 1993 to 1996 of 0.010 and 0.011 mg/kg, respectively. These results are lower than those found in previous studies by WDOH (1996), Tetra Tech (1988), and Faigenblum (1988) who found mercury concentrations in native littleneck clams from 0.01 to 0.06 mg/kg.

Nickel

Nickel was detected in all but one sample, but below the RDL for the majority of the samples analyzed. Concentrations ranged from less than the MDL (0.40 mg/kg) to 1.67 mg/kg, with one exception. The sample at station KSJX02 in 1994 (consisting of bent-nosed clams) had a value of 14.50 mg/kg, which is almost nine times higher than the next highest value. At noted for chromium, this difference can be attributed to species composition of the sample. Nickel is a trace metal not often analyzed in clams, and therefore, comparisons with other studies are not possible.

Silver

Silver was detected in most samples at concentrations above the RDL. Values ranged from less than the MDL (0.08 mg/kg) to 2.18 mg/kg. The highest concentration was detected at station KSSN04. Similar values were found for all years.

Zinc

Zinc was detected in all samples above the RDL for all years. Values ranged from 6.4 to 19.0 mg/kg. Concentration ranges were similar for all four years. The highest concentration was found at station KSUR01. This station also had the highest mean concentration (15.0 mg/kg) between 1993 and 1996. Concentrations detected are similar to those found in other Puget Sound studies (WDOH, 1996; Faigenblum, 1988).

Discussion

Yearly mean trace metal concentrations (all sites combined) varied only slightly between 1993 and 1996 and the highest concentration for any specific metal was not consistently found at one particular site. Of the nine metals presented in this paper, chromium, copper, silver, and zinc were detected above RDLs in most of the clam tissues analyzed from all eight sites and for all years (1993–1996). Copper, chromium, and zinc were detected in all samples; however, chromium concentrations were below the RDL but above the MDL for three samples. Silver concentrations were above RDLs for all but six samples and were not detected in two samples collected in 1994. These results suggest that copper and zinc tend to bioaccumulate to a greater extent than other metals, which agrees with results obtained from other bivalve studies in Puget Sound (WDOH, 1996; Faigenblum, 1988).

State and federal criteria do not exist for acceptable levels of trace metals in shellfish tissues. The U.S. Food and Drug Administration (FDA), however, has established guidance values termed Levels of Concern for both mollusks and crustaceans for five metals: arsenic, cadmium, chromium, lead, and zinc. These guidance values are risk-based and differ for adults and children. To compare results obtained from King County beaches, the lower of the two guidance values for mollusks was chosen. For chromium, this guidance value is 11 mg/kg, which is well above the concentrations obtained from King County monitoring of edible clams (FDA, 1993a).

Table 1. Trace metal data for clam tissues.

Locator	Date Collected	Arsenic (mg/kg wet wt.)	Cadmium	Chromium	Copper	Lead	Mercury	Nickel	Silver	Zinc
KSHZ03	Sep-93	2.5	0.10	0.27	1.90	<MDL (0.3)	0.008	0.50	1.20	12.0
	Jul-94	1.3	0.21	0.21	0.89	<MDL (0.6)	0.004	<MDL (0.4)	<MDL (0.08)	15.0
	Jul-95	2.0	0.27	0.37	1.58	<MDL (0.3)	0.005	0.34	0.07	12.5
	Jul-96	1.8	0.25	0.19	0.95	<MDL (0.3)	0.007	0.31	0.31	13.1
	Mean:	1.9	0.21	0.26	1.33	<MDL	0.006	0.38	0.52	13.2
KSJX02	Sep-93	1.0	0.10	0.20	1.60	0.4	0.005	0.80	1.00	7.5
	Jul-94 *	2.4	0.10	31.30	3.19	1.0	0.008	14.50	0.16	15.7
	Jul-95	1.8	0.16	0.50	1.41	<MDL (0.3)	<MDL (0.004)	0.48	0.12	7.4
	Jul-96	2.1	0.22	1.02	1.90	0.5	0.007	1.22	1.74	6.4
	Mean:	1.8	0.14	8.26	2.03	0.6	0.007	4.25	0.76	9.2
KSLU03	Sep-93	2.0	0.08	0.38	2.70	0.4	0.007	0.80	1.20	14.0
	Jul-94	1.8	<MDL (0.06)	1.02	1.76	<MDL (0.6)	0.006	1.10	0.52	10.4
	Jul-95	2.1	0.05	1.13	1.16	0.5	0.004	0.97	0.11	7.7
	Jul-96	2.8	0.09	0.34	2.08	<MDL (0.3)	0.006	0.92	1.08	17.6
	Mean:	2.2	0.07	0.72	1.93	0.5	0.006	0.95	0.73	12.4
KSSN04	Sep-93	2.7	0.07	0.53	2.20	<MDL (0.3)	0.010	1.00	1.80	13.0
	Jul-94	2.5	0.09	0.62	2.22	<MDL (0.6)	0.010	1.10	1.88	11.7
	Jul-95	2.8	0.07	0.48	1.85	<MDL (0.3)	0.007	0.83	0.89	14.7
	Jul-96	3.4	0.09	0.44	4.72	<MDL (0.3)	0.012	0.92	2.18	14.3
	Mean:	2.9	0.08	0.52	2.75	<MDL	0.010	0.96	1.69	13.4

Table 1. (continued)

KSSN05	Sep-93	2.0	0.10	0.55	2.00	0.4	<MDL (0.004)	1.00	0.10	10.0
	Jul-94	1.6	0.21	1.11	1.72	<MDL (0.6)	0.005	1.20	<MDL (0.08)	12.5
	Jul-95	3.1	0.09	0.48	2.14	<MDL (0.3)	0.008	0.74	0.92	15.4
	Jul-96	1.3	0.19	1.42	1.97	0.5	0.005	1.67	0.08	8.2
	Mean:	2.0	0.15	0.89	1.96	0.5	0.006	1.15	0.37	11.5
KSUR01	Sep-93	2.0	0.10	0.66	5.10	0.4	0.010	1.20	0.28	19.0
	Jul-94	2.6	0.08	0.68	2.60	<MDL (0.6)	0.010	0.83	1.32	13.2
	Jul-95	3.4	0.04	0.60	2.91	<MDL (0.3)	0.009	0.77	1.90	13.6
	Jul-96	2.9	0.07	0.41	1.65	<MDL (0.3)	0.014	0.91	1.45	14.0
	Mean:	2.7	0.07	0.59	3.07	0.4	0.011	0.93	1.24	15.0
LSKR01	Sep-93	2.0	0.15	0.69	3.10	0.6	0.006	1.20	1.20	11.0
	Jul-94	3.2	0.11	0.61	1.57	<MDL (0.6)	0.009	0.86	1.20	13.9
	Jul-95	1.6	0.20	0.94	1.28	<MDL (0.3)	0.005	0.94	0.56	8.3
	Jul-96	3.1	0.08	0.41	2.04	<MDL (0.3)	0.007	0.78	0.97	12.7
	Mean:	2.5	0.14	0.66	2.00	0.6	0.007	0.95	0.98	11.5
LSKS01	Jul-94	2.4	<MDL (0.06)	0.85	1.51	<MDL (0.6)	0.007	0.92	0.83	13.4
	Jul-95	2.4	0.14	0.51	1.37	<MDL (0.3)	0.006	0.75	0.66	11.8
	Jul-96	3.1	0.06	0.29	1.78	<MDL (0.3)	0.007	0.71	0.68	12.1
	Mean:	2.6	0.10	0.55	1.55	<MDL	0.007	0.79	0.72	12.4

Highlighted values were below the reported detection limit but above the method detection limit (MDL).
*Indicates sample was composed entirely of a non-target species, *Macoma nasuta*.

Arsenic, cadmium, and nickel were detected in most samples, but at concentrations below the RDLs. The results are in agreement with arsenic and cadmium values obtained from other Puget Sound studies (WDOH, 1996; Cubbage, 1991). Nickel is not a trace metal often reported, and therefore, comparisons with other Puget Sound studies cannot be made. The FDA Levels of Concern for arsenic, cadmium, and nickel are 55, 3, and 80 mg/kg, respectively (FDA, 1993b, 1993c, 1993d). Results from our sampling efforts are well below these guidance values for all three metals.

Mercury was detected in most samples, however, all concentrations were below the RDL and the mean concentration at each site between 1993 and 1996 was 0.01 mg/kg. The FDA has established an Action Level (above which a food product cannot be commercially traded) in fish and shellfish tissues of 1.0 mg/kg for mercury (FDA, 1985). When this value is exceeded, the food product cannot be commercially traded which is how an Action Level differs from a Level of Concern. All sample results from this study were well below this Action Level. Results are similar to results from previous studies in Puget Sound, which also found values close to analytical detection limits (WDOH, 1996; Cubbage, 1991).

Lead was only detected in eight samples and at concentrations below the RDL. These results are similar to those from previous studies, although the detection limits for our samples were higher than other studies (WDOH, 1996; Faigenblum, 1988). The FDA Level of Concern guidance value for lead is 0.8 mg/kg. All results obtained for edible target species were below this value.

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Results of a Survey on Seafood Collection and Consumption from the Shores of the Duwamish River and Elliott Bay

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Introduction

The Duwamish River and Elliott Bay are highly developed urban water bodies within the city of Seattle that still sustain large recreational fisheries (NOAA, 1987; WADOH, 1985). Many steps have already been taken to remediate chemically contaminated sediments and reduce the release of toxic chemicals in the area. However, chemical contamination in seafood collected from the Duwamish River and Elliott Bay continues to be observed. The presence of potentially toxic chemicals in seafood from the Duwamish River and Elliott Bay raises concern about the level of risk to recreational anglers posed by eating chemically contaminated seafood collected in this area. These individual risk levels can be estimated using standard risk assessment techniques.

King County is conducting the Duwamish River/Elliott Bay Water Quality Assessment to assess potential risks to people arising from exposure to chemicals or pathogens, to wildlife from chemicals and to aquatic life from chemicals and physical stressors (e.g., low dissolved oxygen) in the river and bay (King County, 1997). The Water Quality Assessment is also estimating the relative proportion of risks contributed by CSO discharges. As part of this project, human health risks from exposure to chemicals through consumption of chemically contaminated seafood are being estimated.

To estimate chemical exposures from seafood consumption both the chemical concentrations in seafood and the amount and type of seafood consumed must be estimated (USEPA, 1989). A comprehensive sampling and analysis program was implemented by King County to obtain chemical concentration data in the tissues of salmon, rockfish, English sole, mussels, shiner perch, red rock crab, prawns and squid. A seafood collection and consumption survey was also conducted to estimate the types and amount of different seafood collected and consumed from the river and bay.

Several studies have been conducted that examined seafood collection and consumption in Puget Sound (NOAA, 1987; WADOH, 1985; Toy et al., 1996; Pierce et al., 1981). These studies suggest that many people continue to collect seafood from Puget Sound, both from the shore and from boats. Two of these studies included surveys of fishers in Elliott Bay (NOAA, 1987; WADOH, 1985).

The survey conducted by King County was designed to supplement the information collected from Elliott Bay during the mid-1980s. King County surveyed individuals collecting seafood from the shores of the river and the bay. Boaters were not interviewed because limited boat fishing is expected to occur within the bay, especially for salmon, because of restrictions on the boat fishing salmon harvest. The survey was designed to provide data from which we could calculate seafood collection and consumption rates. These data will be used in the risk assessment to assess whether there are risks to people from consuming seafood from the Duwamish River and Elliott Bay, and the fraction of the risks attributable to CSO discharges.

Methods

Seafood collection and consumption was estimated for people that collected seafood from the shores of the Duwamish River and Elliott Bay. Both resident and nonresident anglers were surveyed, although it is believed that nonresident anglers will collect and consume seafood from the area less frequently than resident anglers. No effort was made to identify whether the angler possessed the proper license, or was otherwise illegally collecting seafood.

Surveyors were trained on filling out the forms and approaching potential respondents. Surveyors

wore no badges, caps, or other items that identified them as county employees. Surveyors worked in teams of two, and approached every individual they observed collecting seafood within the study area. The survey form was translated into three languages to allow for persons uncomfortable with English to participate in the survey.

Locations where seafood collection could potentially occur were identified during a pre-survey site reconnaissance. These access sites were used as survey locations. During the survey, each of these identified access sites were visited at least twice (AM and PM) each survey day.

Surveys were conducted on 30 days during a 10-week period beginning Sunday, June 22, 1997, and ending Saturday, August 30, 1997. Surveys were conducted every Saturday and Sunday (10 days each), and on 10 weekdays. Weekend days were emphasized because the reconnaissance and results of other surveys (e.g., NOAA, 1987) indicated that a substantially larger number of people collected seafood on weekends.

Each survey day was divided into two shifts. On weekends the first shift began at 5 AM and lasted until 1:00 PM and the second shift began at 12:00 PM and lasted until 8:00 PM. On weekdays the first shift went from 5:00 to 11:00 AM, and the second shift lasted from 4:00 to 10:00 PM. Each shift visited every access point at least once. In an attempt to obtain more complete results, access points with the heaviest activity (i.e., Seacrest Park, Elliott Bay Pier, and Harbor Island) were often visited more than once during a shift.

Survey Design

The design of the survey focused on asking anglers the types of seafood they collected and consumed from the study area, and how frequently they did so. The survey consisted of a three-page questionnaire filled in by the surveyor. When allowed, surveyors also identified, measured and weighed any organisms already collected.

Each respondent was asked whether they had previously participated in the survey, and whether they were willing to participate in the survey that day. Even when an angler declined to participate, some information was often gathered. Each angler was also asked to report age, sex and ethnicity.

To provide data on consumption rates, each angler was asked how frequently they collected and consumed seafood from the survey location each month of the year. Recall questions on the type and quantity of seafood collected and consumed during the past week were also asked. For any organisms collected the day of the survey, their plans for use were investigated. If the angler anticipated consuming the organism, the number of people with which they would share it was asked, as was their anticipated preparation method, and whether anybody sharing in its consumption would be under 10 years old.

Results

A total of 1,947 interviews were attempted during the survey. Many people were approached more than once. Fewer than 1,183 different individuals were approached, with the rest of the interviews being repeat contacts. About 81% of the different individuals agreed to be interviewed on the first time they were contacted, while 19% of the 764 repeat contacts agreed to be interviewed. This resulted in an overall success rate of about 56%. However, the surveyors were often able to gather information for many questions even when the person declined to be interviewed. There were also instances when some questions were not answered, even after the person agreed to be interviewed.

Repeat interviews were more successful when the interviewer was female (34% success) versus male (5% success). No obvious differences in success rates were observed between male and female interviewers on initial contacts. With only 92 of the 1,947 survey responses indicating a communication problem, the use of English-speaking interviewers did not appear to limit our ability to adequately conduct the survey. The majority of the interview attempts took place between either 5 to 10 AM (700 attempts) or 4 to 8 PM (645 attempts).

Survey Locations

A total of 24 survey locations were identified during the initial reconnaissance. Of these, three locations shown on Figure 1 (Seacrest Park in West Seattle, Elliott Bay Pier at the northwest end of Myrtle Edwards Park, and Harbor Island) accounted for 92% of the interview attempts (1792 out of 1947 surveys). Fewer than 35 people were interviewed at each of the remaining sites.

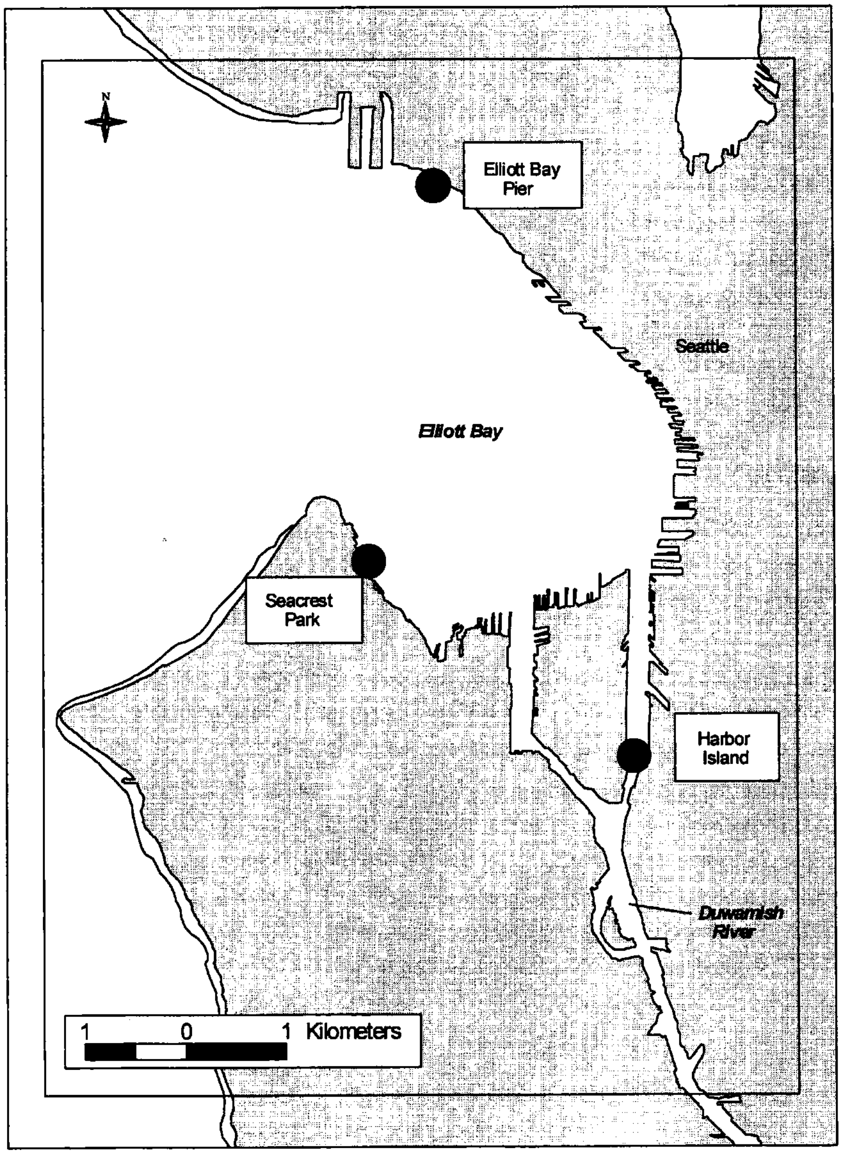

Figure 1. The three most popular seafood collection sites along the shores of the Duwamish River and Elliot Bay in Seattle, Washington.

Age and Sex

The majority of the people surveyed were male (85%) and either 15 to 30 years old (35%) or 30 to 50 years old (43%). Smaller percentages of people surveyed were less than 15 years old (7.7%) or over 50 years old (11%).

Ethnic Background

The majority of the respondents were Caucasian (41%), followed by African American (11%), Filipino (7.8%), Japanese (6%), Vietnamese (5.8%, and Chinese (4%). A wide variety of other ethnicities were also reported.

Time Spent Collecting Seafood

The lengths of time that the people had been collecting seafood when the surveys began were indicated on 1,093 of the 1,947 survey forms. The majority of the people surveyed (53%) had collected seafood for less than one hour. Twenty-one percent had been collecting for one to two hours, and 21% had been collecting between two and five hours. Less than five percent had been collecting for greater then five hours when the survey was conducted. Three people responded that they had been continuously collecting seafood for between 15 and 30 hours.

Seafood Collection Frequency

The majority of the people interviewed collect seafood only in the summertime, although approximately 10% of the people responding collect seafood every month of the year (Figure 2). These results were combined with the frequency that they collect each month to estimate the number of days they collect organisms from the survey location each year (Table 1). Approximately 53% of the 948 different people responding collect seafood less than 12 times per year, about 29% collect between 12 and 52 times per year, and 18% collect more than 52 times per year.

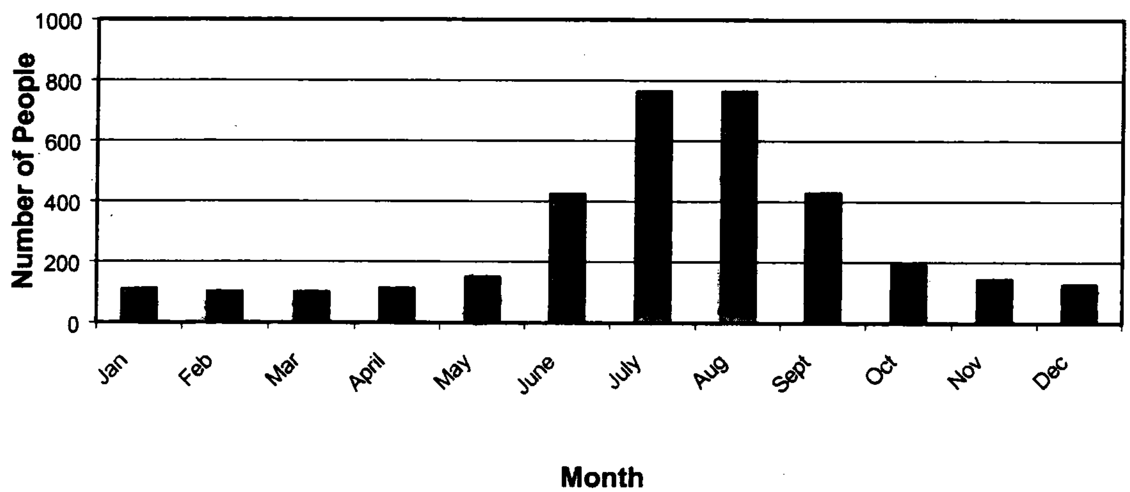

Figure 2. Number of people that collect seafood each month (out of 947 unique respondents)

Seafood Consumption

About 97% of the 942 people responding indicated that they eat seafood. However, only 78% of the respondents stated that they eat seafood that they collect themselves, and only 452 people indicated that they eat seafood from the survey location.

We assumed that people that consume seafood would do so each month that they collect seafood. Based on this assumption, we combined the data on the months that people collect seafood with data on the number of meals they consume each month to estimate the number of days they consume organisms from the survey locations. Most (57% of the 452 people that said they eat seafood collected from the survey locations) consume seafood less than 12 times a year (Table 1). However, a large range was

observed, with twelve people stating that they eat seafood from the Duwamish River or Elliott Bay at least every other day, including seven that consume seafood every day.

Table 1. Frequency with which 1,183 people collect and consume seafood from the survey location.

	Collect Seafood		Consume Seafood	
Frequency (days/year)	Number of People[a]	Percent Of People[a]	Number Of People[a]	Percent of People[a]
0	0	0	466	39.5
0.1-0.9	10	0.8	1	0.08
1 - 1.9	230	19.4	78	6.6
2 - 5.9	174	14.7	114	9.6
6 - 11.9	87	7.4	65	5.5
12 - 23.9	118	9.97	69	5.8
24 - 51.9	157	13.3	72	6.1
52 – 179.9	140	11.8	41	3.5
180 – 365	32	2.7	12	1.0
No Response	235	19.9	265	22.4

[a] out of 1,183 people surveyed.

Seafood Collected

When asked whether they had recently collected seafood that had not been recorded on any survey, 209 people said that they had collected one or more type of seafood from the survey location. Of these 107 people reported that they had collected salmon, 27 collected crabs and 21 collected flounder. Dogfish, herring, ling cod, shrimp, perch, squid, rockfish, sole, sculpin, octopus, sturgeon and candlefish were each caught by fewer than 20 people.

Table 2. Number of people that had collected each species of seafood, and the number and weight collected.[a]

Species	Number of people that collected each species	Number collected	Total weight (pounds)	Average weight per organism (pounds)	Average seafood weight per person who collects (pounds)
Halibut	1	4	3	0.75	3
Clams	1	25	6	0.24	6
Crabs	42	148	>90.2	0.61	2.1
Flounder	12	15	8.4	0.56	0.7
Gunnel	1	1	0.25	0.25	0.25
Herring	8	55	5.1	0.09	0.64
Ling cod	1	1	ND	ND	ND
Shrimp	11	282	>6.25	0.02	0.57
Moon snail	1	1	ND	ND	ND
Perch	19	238	>61.3	0.26	3.23
Squid	2	7	5.1	0.73	2.55
Rockfish	9	9	8.75	0.97	0.97
Sole	11	22	5.6	0.25	0.51
Salmon	33	34	>364.25	10.7	11.04
Sculpin/bullhead	9	10	2.6	0.26	0.29
Candlefish	1	30	ND	ND	ND

ND = No data available

aOut of 1,218 people responding

When asked whether they had collected seafood on the day they were interviewed 1,218 people responded. Of these, about 14% had successfully collected any seafood. However, the actual success rate is likely to be higher, because the people interviewed generally continued to collect seafood after the interviews. Initial review of the data indicates a greater success rate for longer collection times.

The number of people that had already collected seafood, the number of each species collected and the total and average weights of each seafood type collected are presented in Table 2. The species collected by the most people were crabs, followed by salmon and perch. Although collected by fewer people, shrimp and perch, along with crab, had the highest numbers collected. Salmon contributed the greatest portion, by weight, of seafood collected (64% of the total), followed by crabs (16%) and perch (11%). Seacrest was the most productive site, with more (numbers and pounds) of crab, shrimp, perch and salmon collected here than at any other location.

Planned Use of Collected Seafood

One hundred and thirty four people indicated during their interviews what they intended to do with the seafood that they had collected. Most (74 of 134) of these people stated that they planned to eat their catch and share it with others. The remaining people stated that they would eat the seafood alone, use it as bait, release it, give it away, or responded "other." When asked about the number of people that would share the meal, 87 people stated that they would share the seafood with a total of 365 people. Twenty-seven respondents also stated that they would share the seafood with children under the age of 10.

When asked what parts of the fish would be eaten, 43 out of 69 people responding (62%) stated that they would eat the meat only, 20 said that they would eat the meat and skin, and six said they would eat the whole fish. When asked what parts of the shellfish would be eaten, all (43 out of 43) respondents said they would eat the meat only.

Baking or frying fish was preferred 4:1 to grilling fish. Other fish preparation methods (e.g., boiled) were even less preferred. Crabs, shrimp, and clams were usually boiled or steamed.

Discussion

Based on the questions on consumption frequency, 50% of the 452 people responding that they eat seafood from a specific survey location less than eight meals a year. The national mean intake of seafood per meal is estimated to be about 4 to 4.5 ounces (117 to 129 grams), while the 95th percentile[x] intake ranges from about 10 to 11.5 ounces per meal (284 to 326 grams per meal) (USEPA, 1996). Using these estimated meal sizes, 50% of the people consume an average of less than 36 ounces per year (1 kg per year) to a 95th percentile of about 86 ounces per year (2.4 kg per year) of seafood from the survey locations each year. These consumption rates are similar to the estimated average consumption rates for recreational marine anglers of 25.7 to 91.7 ounces per year (0.73 – 2.6 kg per year) (USEPA, 1996).

Using the same average and 95th percentile seafood meal sizes, the seven people who consume seafood from the survey locations every day consume an average of about 102.6 pounds per year (46.6 kg per year) and a worst-case scenario of about 245 pounds per year (111 kg per year). These consumption rates are substantially larger than the worst-case consumption rates for recreational marine anglers of 21 pounds per year (9.5 kg per year) (USEPA, 1996). These consumption rates are similar to those estimated by the USEPA (1996) for subsistence populations. This indicates that there is a small population of people that collect seafood from the shores of the Duwamish River and Elliott Bay that may be considered "subsistence" anglers (USEPA, 1996).

The 452 people that consume study area seafood eat a grand total of 11,354 seafood meals from the Duwamish River or Elliott Bay per year. Of these, the seven people that eat one seafood meal per day (1.5% of the respondents) account for 20% of the total number of meals of Duwamish River/Elliott Bay seafood each year. Similarly, 42% of all such meals are consumed by 27% of the respondents (125 out of 452 respondents).

The size of the population that consumes seafood collected from the shores of the Duwamish River and Elliott Bay is actually larger than the observed population (Price et al., 1994; USEPA, 1996). We have not estimated the total population of people that collect and/or consume seafood from the shores of the Duwamish River and Elliott Bay because it is likely that the average exposures for the total population will be below the average exposure for the observed population. For risk assessment purposes, use of conservative exposure estimates is warranted.

The type of seafood collected is expected to vary throughout the year. For example, returning salmon may only be caught from the shores of the river and bay during the summer and fall. Squid are fished during the winter, when they come close to shore to feed and spawn. Blackmouths (juvenile salmon) are caught during the winter only. These changes in seafood availability likely influence the numbers of people that collect organisms each month and the chemical concentrations to which people are exposed. An informal inquiry into the squid fishery indicates that many people that collect squid during the winter do not collect seafood during the summer. This implies that Figure 1 may underestimate angler pressure in winter months.

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[xx] The 95th percentile intake rate represents an intake rate that is greater than that sustained by 95% of the people. This value is an approximation of the maximum consumption rate.

Real-World Sanitary Survey Results and Correction of On-Site Problems in Two Important Shellfish Growing Areas in Mason County, Washington

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Mason County Enviromental Health

Abstract

Mason County boasts a large number of commercial marine shellfish waters that support the economy of this area. Some years back these shorelines were slowly being closed, one after another, due to unsanitary waters. The suspicion was that domestic septic systems were the largest cause of the marine water degradation. The Lower Hood Canal (LHC) and Totten Little Skookum (TLS) sanitary surveys were the two largest surveys ever undertaken by Mason County to combat the problem. During this work, a wealth of knowledge was gained about what compels people to participate, the real costs involved, and the effectiveness of the surveys.

The Lower Hood Canal Survey was undertaken in 1994. The survey funding came from the LHC Clean Water District assessments created due to the closure of shellfish and other recreation beaches. A staff of six worked for three years on this project. Five thousand surveys later, we had identified 500 septic failures. The causes of the failures varied from items as simple as crushed transport pipes and dilapidated tanks to the need for costly full-system replacements. Once the septics systems were repaired, a marked change in water quality occurred, allowing many of the shoreline areas to be reopened.

The Totten Little Skookum sanitary survey was a preemptive strike by the shellfish growers, clean water district, and health department to ensure that the septic systems in that area would not be a cause of non-point pollution. The survey was co-funded by a grant and the Totten Little Skookum clean water district assessments. The survey lasted from 1993 to 1995.

Suitability of Surrogate Species to Estimate Human Health Risk Due to the Consumption of Nontraditional Marine Resources

Ruth A. Thompson and Burt Shephard
URS Greiner, Inc.

Abstract

The evaluation of potential risks to humans from consumption of contaminated nontraditional marine invertebrate species is complicated by the lack of information on the ability of these species to bioaccumulate contaminants and by the lack of knowledge of population consumption patterns. While traditional species are commonly used as indicators to be surrogates for the nontraditional species, the accuracy of such extrapolations is largely unknown. The sea cucumber is a nontraditional species consumed primarily by Asian and native populations in the Pacific Northwest. This paper evaluates the suitability of two traditional species, clams and crabs, as surrogates of risk incurred by the consumption of sea cucumbers harvested from Ostrich Bay and Sinclair Inlet in Puget Sound. It also examines the ability of sea cucumbers to bioaccumulate chemicals, and it evaluates local consumption patterns.

Questions & Answers

Q: Regarding the survey. Do you know the nationality of the respondents?

A: Yes we do, and we had a very wide range of nationalities reported. About 40 percent of the individuals were Caucasian, followed by African American at probably 15 percent, and then a whole range of different nationalities after that at 10 percent or less.

Q: What nationalities ate the fish daily?

A: That was, again, very similar to the range that we saw. There were a few Caucasian, a few African American, a few Asians, different Asian ethnicities as well.

Q: Given the nationalities represented in respondents, I'm concerned about the language skills of the surveyors. Also, I'd like to know whether you took into consideration that some people might have been afraid to give accurate answers about how often they were eating fish. How did you deal with some of those cultural differences.

A: Our surveyors, in general, spoke English. We had our survey forms translated into foreign languages as well. Vietnamese, Laotian, and others (I don't remember, I'd have to look it up.) But we did have quite a few of those (non-English) forms filled out. We had a mark on the survey where the surveyor would indicate whether or not they perceived a language barrier (e.g., the person that they were interviewing might have been uncomfortable with English). That got filled out on 99 of about 1900 survey forms, so in approximately 5 percent of the surveys, the surveyor perceived a language barrier. As far as the reluctance to give an accurate answer, we didn't have a question where the surveyor could mark down whether or not they thought they were getting an accurate answer. There's really no way to account for that. We tried to make it sound like we were doing a research project. We tried not to come across as government officials. We did not wear badges or caps or anything that would indicate that we were officials, so that we would not put someone off and make them reluctant to give us a truthful answer. We tried to basically go out there and become their friends, in essence, so they would give us the best answers they could.

Q: I'm surprised with your ethnic representation because at Carkeek Park, we observe that people harvesting shellfish are probably about 80 percent Asian. Are you planning to measure fecal coliform levels in shellfish?

A: As far as the survey goes, I would suspect that the ethnicities of the folks collecting seafood would vary from locality to locality, so seeing different ethnicities in a different location is to be expected. I can't comment on the fecal coliform levels in shellfish. Can you comment on that?

A: Yes. We will continue to measure fecal contamination in both intertidal waters and shellfish at Carkeek.

Q: Did your survey ask about food preparation or the amount of the organism consumed or did you just assume a 100 percent consumption rate? If 50 percent of people say they don't eat the organisms, I would kind of wonder why they were investing the energy to fish. Maybe were they selling their catch and were afraid to tell you they were selling it?

A: Yes, we asked both those questions, I didn't present the results here because I was trying to keep the talk short – because I had only 13 minutes. Regarding food preparation, we had one individual who said that they intended to eat some of their seafood raw. The rest of the individuals indicated a preferred cooking method. For fish, it was generally broiled or grilled, or maybe it was baked or grilled. We have the data about what percentage said they were going to do what for fish and shellfish. Regarding the

amount eaten, we asked, "What portion of the collected seafood would you eat?" The vast majority of the folks that we interviewed said just the fillets for the fish, although we did have some folks who said fillets and skin. We also had folks that said they were going to eat the entire organism. As far as what amount was collected, that's a good question. It really seemed, as far as I can tell, that there were a lot of folks that just enjoyed fishing. It is possible that some were selling their catch, but no one ever mentioned it.

Q: Are there King County CSO's at other freshwater sites or are they non-King County CSO's?

A: There are still some freshwater CSO's in the Ship Canal and in Lake Union. Those sites are going to be controlled sooner rather than later, meaning that there are plans already in the works to control those CSO's. The CSO's in Lake Washington, with the exception of one for which controls are being designed right now, have already been controlled. It is our expectation that we will be doing some extensive analysis in the freshwater CSO's. There is a plan that you will be hearing more about in the future.

Q: This discussion of freshwater CSO's raises an interesting question about species that you would use for monitoring. Certainly mussels aren't going to do well in freshwater.

A: There are other bivalves that are found in freshwater that, I think, could be used like we used mussels in marine waters to study bioaccumulation.

Q: The survey is interesting. How do you extrapolate from the data you've collected to an appropriate consumption range within your study area? For instance, you acknowledge that you'd get different species mixes at other times of the year. Also, you didn't survey at night during your ten week survey. I was under the impression that between 8:00pm and 5:00am there were no people surveying. Is that correct?

A: No one was surveying after 10:00pm.

Q: So most of the night period was not covered. So how do you extrapolate if you want to use an appropriate consumption rate within your study area. Are you going to be using other studies? How are going to use the information you've collected?

A: You hit the nail on the head there, Glen, with that question. The question is how to extrapolate from results to determine an appropriate consumption rate for our study. Essentially what we intend to do is to look at our results and come up with a range of consumption rates in combination with results from other studies. There have been studies conducted in Elliott Bay and other parts of Puget Sound dating back to the early 1980's and including a recent study that was conducted for two local tribes. That was conducted back in 1996, I believe. As far as extrapolating our results, there are ways to statistically extrapolate results, assuming we got a representative sample on some days, "how many people did we miss," and all that kind of stuff. At this point, we expect that consideration of these other factors would result in a lower consumption rate than the consumption rate we already have. One of the questions we're asking, or that we're considering, is whether or not it is worth extrapolating beyond what we have already done. For example, fewer people would go out less frequently in the nighttime hours than went out in the daytime hours. We are still looking into it.

Q: Were there any fish consumption advisories during the survey? Will they continue?

A: There is an ongoing advisory against harvesting of shellfish in Elliott Bay. That advisory was present last summer during our survey. I'm not sure, personally, whether or not there are other advisories in the bay. We did not make an attempt to notify people or to check whether or not people were doing anything illicit or illegal. We just wanted to go out there and see what was actually happening,.

Q: To follow up on the not needing to monitor the use of source control, or what ever, in freshwater CSO's, there is a comparable example in the marine environment. A year or so ago

Alan Mearns made an interesting calculation with regards to the decreasing output of zinc from Los Angeles county. At the same time the bioavailability of zinc went up in organisms in the area. So I think that monitoring, just to make sure that your source control has really done what you expect, may be a reasonable thing to consider.

A: That's a very good comment.

Q: When you do the risk assessment, where are you getting the data for the concentrations of fish?

A: The water quality assessment had a very comprehensive sampling program associated with it where we sampled a wide range of fish and shellfish species in Elliott Bay and Duwamish River. A portion of that program was represented by John's talk here on the mussels, but we also sampled a wide range of other species, partly in conjunction with the Department of Fish and Wildlife.

A: Some of the data from that aspect of the work are presented in the poster session. At least for tributyl tin, in a number of fin fish and shellfish species including crabs, prawns and intertidal invertebrates.

Q: I'm interested in the Mason County sanitary survey that Will presented. My impression was that there was voluntary participation in the survey and mandatory repairs to sanitary systems at the owner's expense. How did the politics of that work?

A: It really varied from watershed to watershed. From my observation, it relates to what the project's momentum and, somewhat, on the history of the area. Totten-Skookum was formed as a voluntary shellfish protection district. The shellfish growers chipped in with $36,000 (I think) to help defray the cost. It was a different political climate in lower Hood Canal with some very vocal and active opposition. In lower Hood Canal it spun into a political realm where you got neighbors saying, "Well, if my neighbor is not going to voluntarily do this program, I'll be damned if I will." There was really some divisive stuff and threatened lawsuits. I think Will was quite politic in explaining how it really is important that the front line people are good readers of people's reactions, and that they try to listen. A positive, cooperative spirit as opposed to getting in an argument with somebody, which unfortunately did happen in some of those cases. Those negative words spread real quickly, and pretty soon you get a whole section of a neighborhood up in arms and saying, "Over my dead body will you come onto my land and check my on site system."

Q: Tim, since you found disappointing results, that the water quality seems to be declining in most of those areas, have you gone back to the shellfish protection districts or the watershed planning groups to look at what they are already trying to accomplish, and what else might be on their list that they haven't got around to yet?

A: After I presented these results to managers at Department of Health, I was told to take the results out to show to the local county health people. I have done this in the case of Henderson Inlet; we had a short meeting to discuss my findings. I think that people in the watershed management, or the implementation groups that have been set up, particularly in Henderson, are aware. I don't know whether they have taken it upon themselves to follow through. They haven't asked me to come back to talk to them specifically about it.

Comment: I think some of the work that Tim and others at the Department of Health's shellfish program have done in developing the "early warning system" is really good. They can go and talk to shellfish growers and also to local elected officials and say, "This is what the trends are looking like, and we've got real concerns in this area" before it gets to a downgraded condition. I'm hopeful that this will help us a little to encourage a spirit of cooperation. Ideally, this will allow us find out what the problems are and address them without a downgrade. Early response will be preferable to having a downgrade.

Q: John, you didn't present any time-zero data for wild or transplanted mussels and I'm wondering about that. And I'm curious if there was any CSO discharges during the transplants.

Strand: Regarding the time-zero analyses of the mussels to be transplanted – I do have that data. There wasn't a whole lot of difference between the time-zero and the time-one-month for the transplants that were maintained at the mussel farm where they came form. I just simply collected the wild mussels coincident with retrieval of the transplanted mussels. I didn't have a time-zero for them and a time-one-month. I just collected essentially once during the dry season, once during the wet season. And again, it was coincident with retrieval of the transplanted mussels. Yes, there were discharge events during the wet season; a series of them. That was very wet year; the hydrograph for the river over that one-month period in which the transplants were deployed went from about 2,000 CFS to nearly 10,000 CFS and dropped back down. There were a number of discharges over that period. At the Brandon Street CSO, at the Duwamish Diagonal Way CSO, and the Hanford CSO. We have the actual number tallied, but I can't recall them off the top of my head. But, yes, multiple discharges over that one-month period. There were no discharges over the dry season. The first discharges came late in October after the transplanted mussels were removed from that dry season exposure.

Q: The Mason County survey found maybe 10 percent of the systems were failures, and they found out that 90 percent were OK. Did they make any kind of assessment how that 90 percent tested and how many they missed. Were all the systems really good?

A: I'm not clear from the data that Will presented today. There's a more clear report that the county has done in the past that shows where they've used dye testing at waterfront homes.

Q: In the survey, how did you ask the question about whether or not they were eating the seafood?

A: I'd have to go back and read the survey form again, but I believe that it asked if you would eat what you had actually caught, not just what you were targeting.

Q: Is the survey information broken down by age?

A: We broke it into four categories: "less than 15," "15 to 30," etc. Most of the folks were in the "15-45" age. So there were a few folks under 15 there, but it was a very small percentage. We also asked whether or not they would share the seafood with anyone under 10. We had 27 people total who said that they were going to share their catch with people under 10. So, there are children eating this seafood as well.

Q: Kim, in your compositing of, for instance, native littlenecks clams that you were sampling, did you try and select a certain size clam as a typical size so you'd get uniform samples from one place to another (to account for age effect on concentration)?

A: Samples were not necessarily selected to be the same size, but they had to be of marketable size. The ranges of sizes could have varied, but they tried to minimize the age variation.

Q: John, in the time period that you were looking, did you see a change in growth rate of the transplanted mussels that you got from the farm?

A: With very accurate weighing and sizing we did follow growth both in the dry season and in the wet season as it might related to effects. Clearly the mussels in the dry season grew much more than in the wet season, and the mussels left at the farm grew 65 percent. That's the percent increase in weight from the time that they were transplanted. The mussels in the river grew an average of 20 to 25 percent. There were some differences with location, but they did grow, not nearly as efficiently as the mussels that were kept on the farm. Growth in the wet season decreased significantly from that, but the mussels in the river did grow about 5 percent. The mussels that were kept at the mussel farm at Totten Inlet grew a bit more. There was growth, even in the wintertime.

PUGET SOUND RESEARCH '98

SESSION 2A

THE PHYSICAL SOUND

Session Chair:

Curtis C. Ebbesmeyer
Evans-Hamilton, Inc.

A Numerical Model Of Puget Sound Circulation

Mitsuhiro Kawase
School of Oceanography, University of Washington

Introduction

We report here early results from a numerical model of marine circulation in Puget Sound, which is to form an element in the Puget Sound Regional Synthesis Model (PRISM) project at the University of Washington. PRISM is a project supported by the University of Washington University Initiative Fund (UIF), and its aim is to develop and consolidate university-wide expertise in the Puget Sound region's natural and human environment. The circulation model is fully three-dimensional, and is designed for reproducing the Sound's circulation over tidal to interannual time scales. We intend to develop a predictive capability for Puget Sound circulation pertinent to such issues as water quality, pollutant dispersal, and harmful algal bloom development. It is our intention to make this model eventually a component of a regional earth systems model in which it would interface with meteorological and hydrological models and would incorporate models of biological productivity and transport of contaminants.

The Model

The circulation model is based on the Princeton Ocean Model (POM, Blumberg and Mellor, 1987), which has been used extensively in coastal and estuarine studies. The model equations are those of the standard primitive equation (hydrostatic) dynamics. Given initial and boundary conditions, the model predicts in time sea-surface elevation, three components of circulation velocity, temperature and salinity as well as turbulent kinetic energy and turbulent mixing length. The latter two are used in parameterizing vertical eddy mixing in terms of turbulence closure scheme of Mellor and Yamada (1974). Surface elevation and depth-averaged velocities are integrated separately from internal quantities in a split-explicit formulation.

The model domain (Figure 1) covers the entire Puget Sound from Admiralty Inlet inwards, as well as a part of the Strait of Juan de Fuca, at a 600-m resolution in the east-west direction and 900-m in the north-south direction. Bathymetric data were supplied at 300-m resolution by Dr. Miles Logsdon of the School of Oceanography, University of Washington. The data were then subsampled at model grid points. This resulted in inadequate resolution at several locations. Bathymetry was further manipulated at these spots as follows:

- Branch channels and inlets that could be represented by only one grid point across were blocked, and isolated bodies of water thus formed were filled, except:
- Hood Canal at Sisters Point was enlarged.
- Islands with only one grid point and fully surrounded by water were eliminated.

In addition, cut-off was made at ten meters depth, eliminating much of shallow tidal flats; the current version of the model does not handle wetting/drying during a tidal cycle. Ocean depth in the Strait of Juan de Fuca was set to 100 m. The region outside of Admiralty Inlet is intended as a holding area in this model and is not actively modeled.

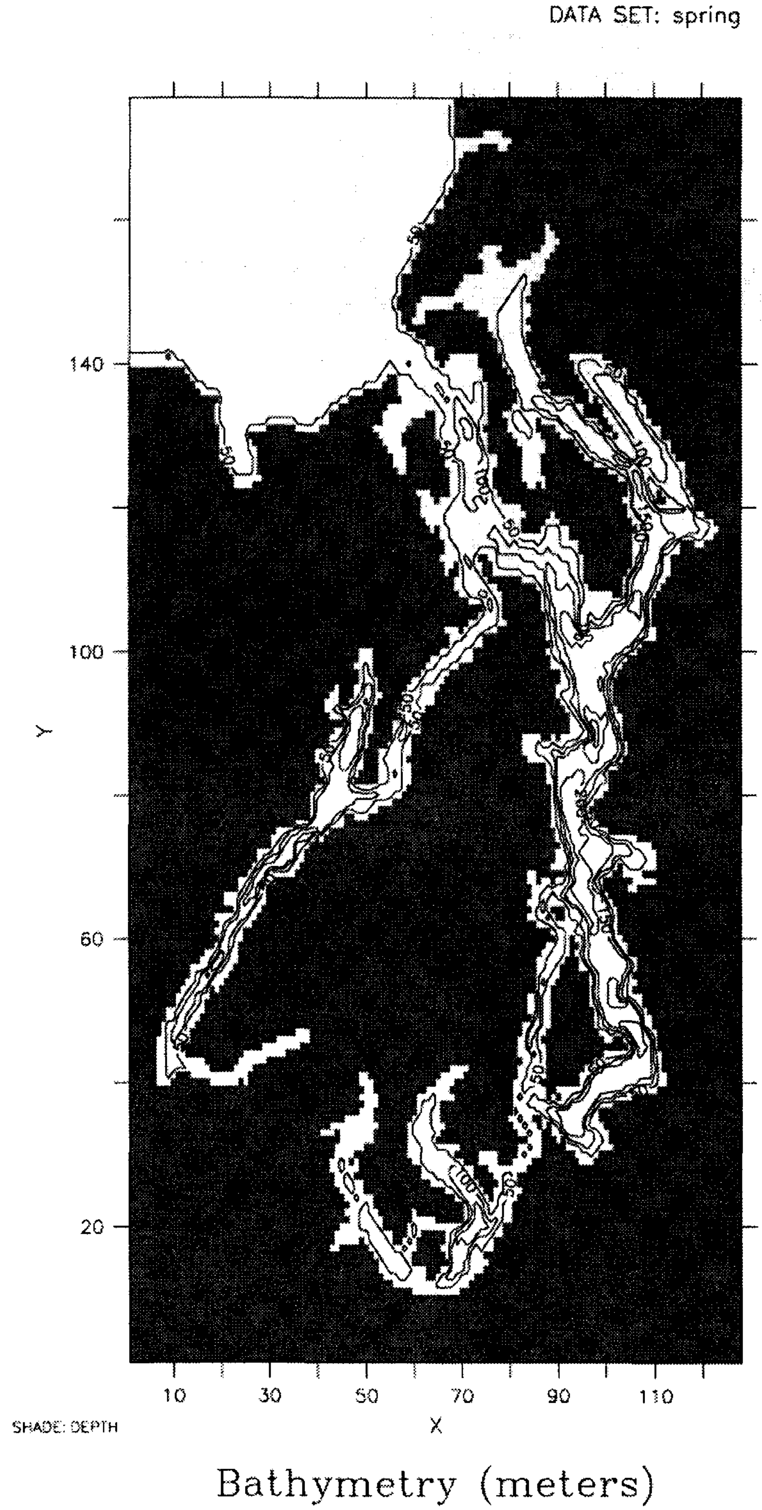


Figure 1. Model Domain and Bathymetry.

The model responds to wind stress, heat, and fresh water fluxes applied at the sea surface as surface boundary conditions. Boundary conditions at the bottom are no mass, heat and salt flux, and bottom stress in terms of quadratic drag. River input is specified as mass and fresh water sources at

grid points nearest to the geographical locations of river mouths. The model has an open boundary in the Strait of Juan de Fuca, where tidal forcing is incorporated as boundary conditions using Flather's (1976) scheme. Seven tidal constituents (M2, K1, S2, N2, O1, P1, M4) were used in forcing, in emulation of an earlier channel model of Puget Sound tides by Lavelle et al. (1988). In addition, a radiation boundary condition was applied to external and internal modes of velocity, while temperature and salinity were either advected out or set to a prescribed value when advected in.

Results

In this proceeding, highlights from the model's barotropic tidal circulation will be reported. This is by no means an exhaustive verification even within this restricted scope; the richness and complexity of the model's response, as well as the wealth of data available for the Sound, opens many further avenues of comparison.

Sea Level

Time series of sea level were generated at 43 grid points that correspond to locations of a subset of tidal stations reported by Lavelle et al. (1988). They were regressed against the seven forcing frequencies and resultant amplitude and relative phase of each tidal constituent were compared with observed amplitude and relative phase. (By relative phase we mean phase value relative to an arbitrary base line; in this case the average of all phase values for a given component.) Figure 2 plots modeled amplitude and relative phase for the semi-diurnal M2 component, which is the most dominant, against the observed for all stations. Overall agreement is excellent for amplitude; the modeled phase range is also in excellent agreement with the observations, but there is a tendency for the modeled phase to cluster around several values, indicating that each sub-basin of the model tends to oscillate more or less in phase within, while in reality the M2 tide shows more propagating tendency. This is indicative of insufficient dissipation of tidal energy in the model, which tends to set up standing oscillations within each basin. Lavelle et al. (1988), in the modeling part of their study, also noted a need for stronger-than-usual dissipation in modeling Puget Sound tides correctly.

Similar agreements were found for other components of the tidal variation of sea level. Figure 3 shows a similar comparison for the K1 component; observations show that, generally speaking, diurnal components have narrower phase lags and more uniform amplitude distributions than semi-diurnal components; this was reproduced well in the model response. The tendency for the model phase value to cluster was more pronounced for diurnal frequencies.

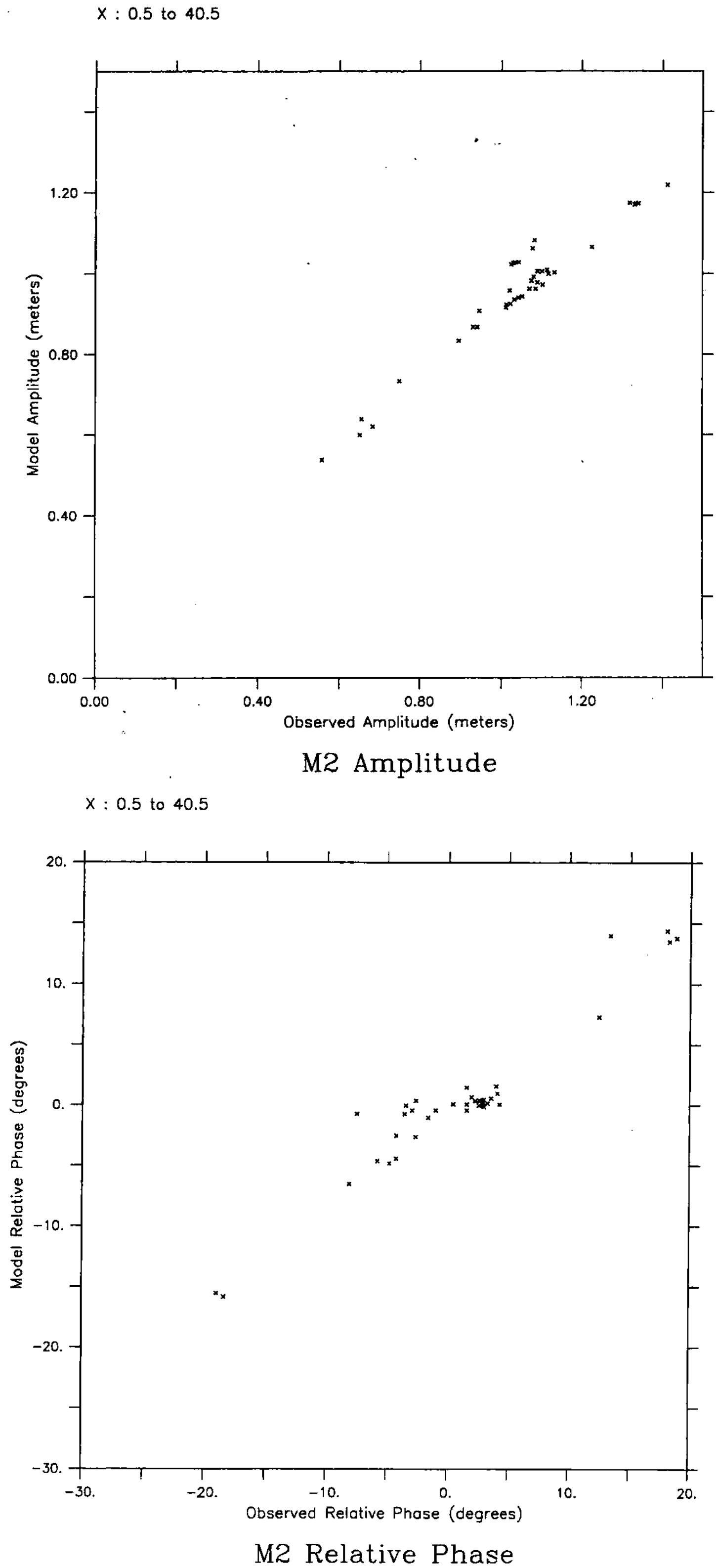
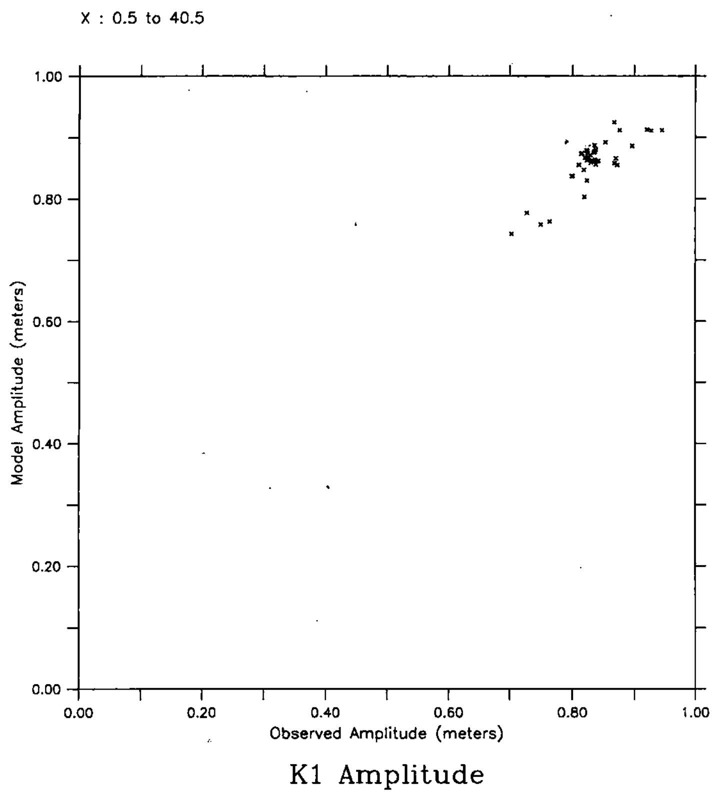


Figure 2. Comparison of observed and modeled M2 tide. Observed (horizontal axis) versus modeled (vertical axis) amplitude (left) and relative phase (right).



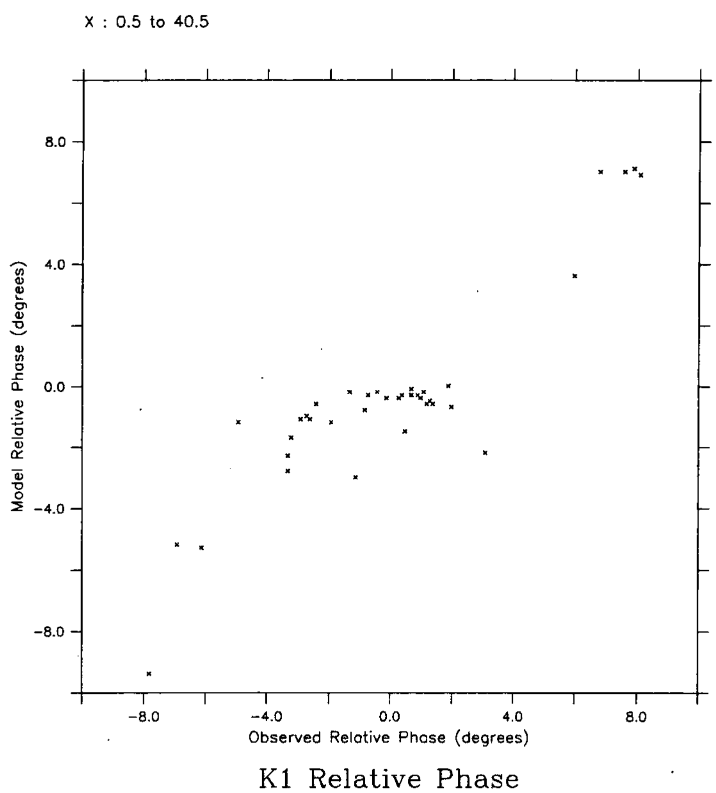


Figure 3. Comparison of observed and modeled K1 tide. As in Figure 2.

Currents

Strong tidal currents occur through Admiralty Inlet and Tacoma Narrows. In addition, strong currents are observed in Hood Canal north of Seabeck Bay. Tidal currents through Admiralty Inlet reach speeds in excess of 2.5 m/sec, while in Tacoma Narrows speeds exceed 2 m/sec and in Hood Canal speeds reach 1m/sec. The maximum current in Admiralty Inlet in the model occurs between Admiralty Head and Point Wilson–Marrowstone Point (Figure 4).

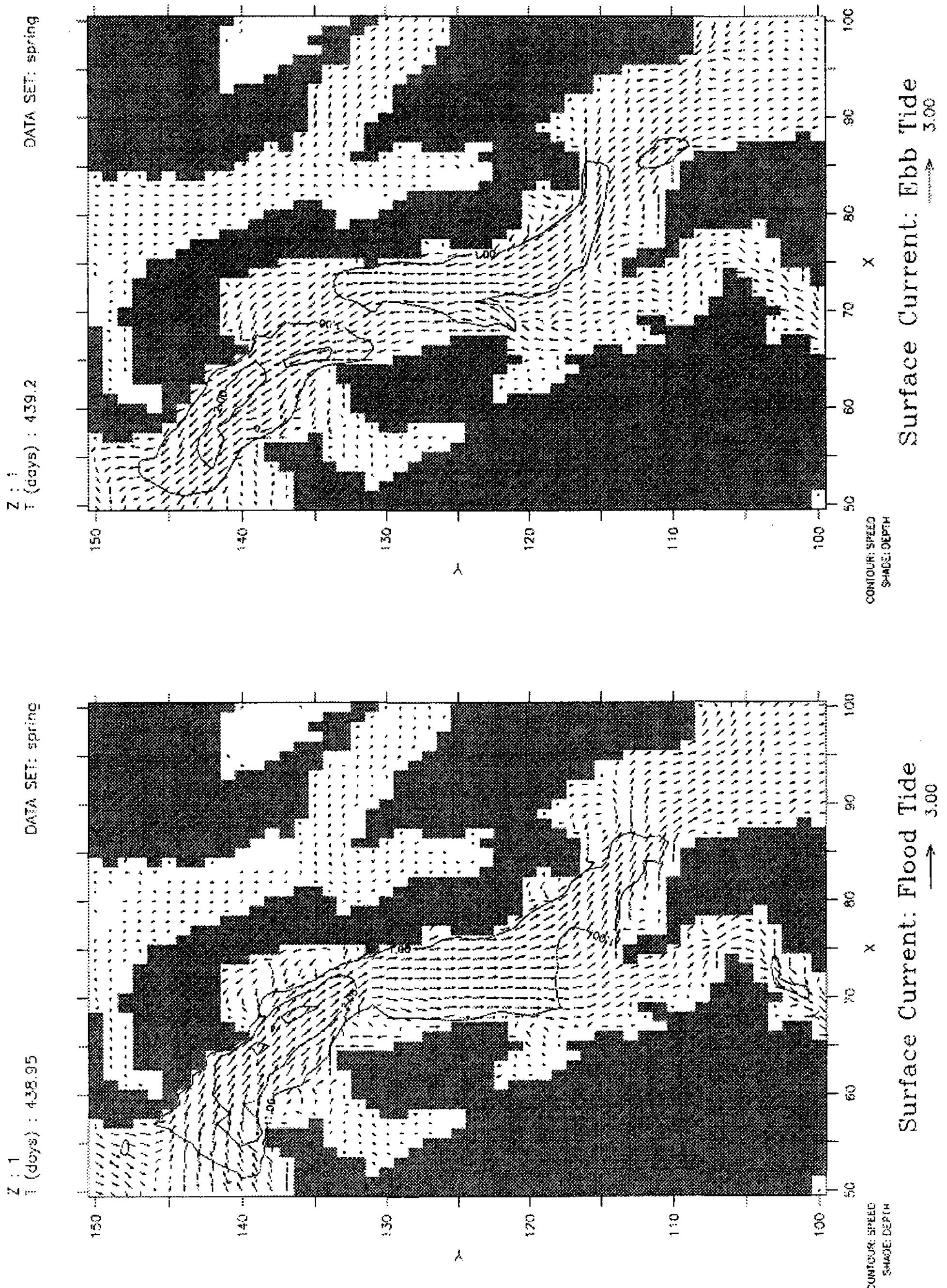


Figure 4. Surface current in Admiralty Inlet. Current direction (vector) and speed (contour). Left: maximum flood tide. Right: maximum ebb tide.

Velocity components were regressed against M2 and K1 frequencies at several points in the model where current meter records exist. Figure 5 shows current ellipses at the surface along an east-west section at Bush Point in the model, which corresponds to a MESA current meter section reported by Cannon et al. (1979) and analyzed by Mofjeld and Larsen (1984). Both M2 and K1 components have realistic semi-major axis amplitudes (1 m/sec for M2 and 45 cm/sec for K1). Moreover, the model reproduces slight intensification of M2 current towards Whidbey Island and maximum of K1 current at the center of the channel, both observed features in the current meter records.

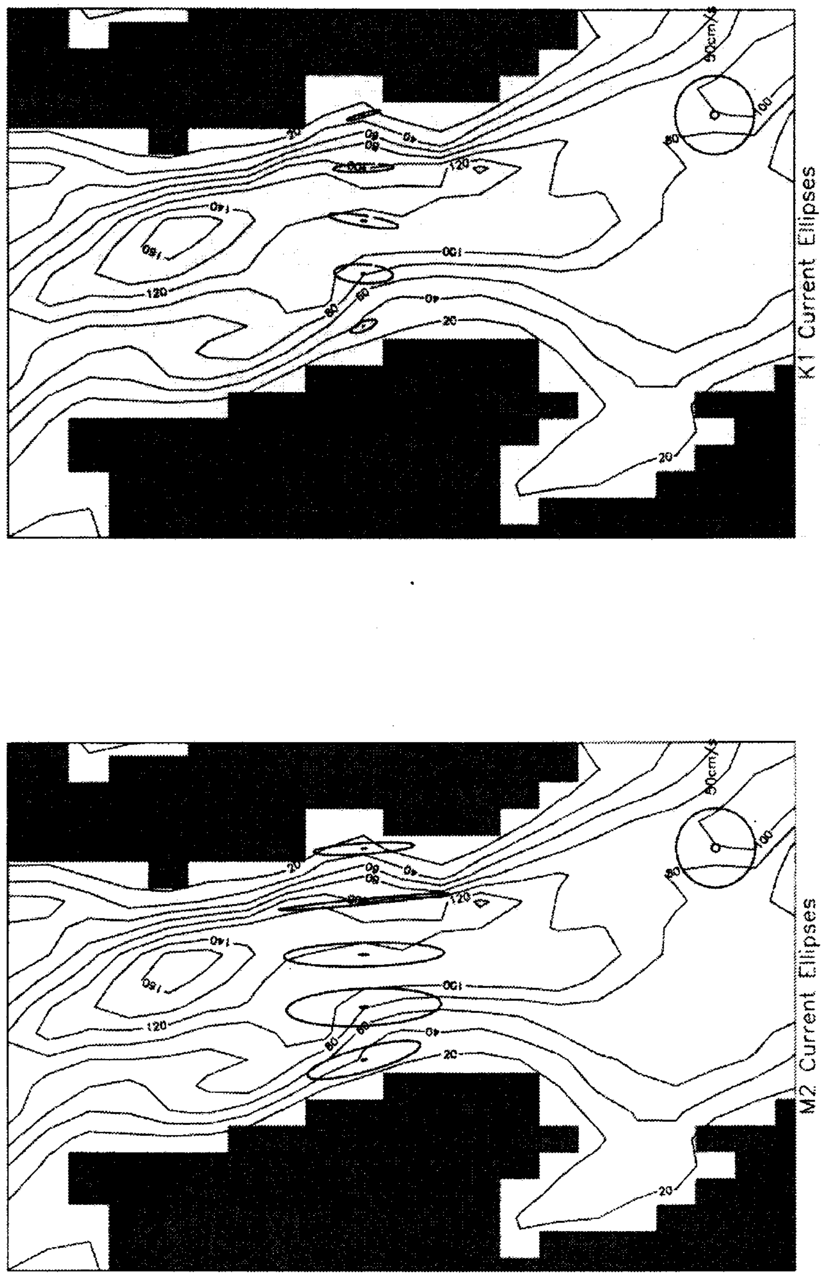


Figure 5. Tidal ellipses in Admiralty Inlet, roughly corresponding to the location of current meter section by Cannon et al. (1979). Left: M2 component. Right: K1 component. Circle in lower right corner indicates current amplitude of 50 cm/sec.

Eddies

Several tidal eddies appear in the model, most notably in Admiralty Inlet off the main axis of the tidal flow. An anticlockwise eddy appears during flood tide in Admiralty Bay and similarly in Useless Bay (see Figure 4). The amplitude of the currents associated with these eddies is typically of the order of 40 to 50 cm/sec. These eddies are clearly generated at headlands and captured in coves that lie downstream of them; due to the geometry of the west coast of Whidbey Island, they tend to be pronounced during flood tide.

Another notable feature in the model, striking in the model animation, is a propagating, coastally trapped wave along the western shore of southern Whidbey Island that recurs every tidal cycle. Apparently this wave is generated at the southern end of Whidbey Island at the beginning of ebb tide and propagates into Useless Bay, where it appears to dissipate.

Conclusions

The three-dimensional model of Puget Sound circulation has been successful in reproducing many aspects of the observed tidal circulation of the Sound, while its rich detail is suggestive of further observational verification. The river- and wind-driven components of the circulation also await further investigation and verification with data. We believe the circulation model will become a useful tool in understanding the physical working of the Sound and the circulation's role in the overall marine environment.

Acknowledgments

The author thanks Washington Sea Grant and University Initiative Fund for financial support for the development of the model. Jeff Richey was the motivational force behind PRISM, and Parker MacCready has been a constant source of input and encouragement. Miles Logsdon supplied bathymetric and river discharge data. Mark Stoermer produced excellent model animations that were presented at the Conference. Other graphics in the talk and in this proceeding are produced using the graphics package FERRET from NOAA/PMEL.

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High Resolution Seismic Reflection Interpretations of the Hood Canal-Discovery Bay Fault Zone, Puget Sound, Washington

Brian J. Haug
Portland State University

Introduction

Hood Canal, an elongate, 75 km-long, two- to five-km-wide, northeast trending deep-water trough, defines the western limit of the Puget Sound estuary complex (Figure 1). This glacially and subglacially-carved feature, one of many channeled landforms occupying the Puget-Fraser Lowland, is filled with thick Quaternary deposits of unconsolidated and semi-consolidated glacio-lacustrine, glacio-fluvial, and transgressive marine sediment (Eyles et al., 1990; Mullins et al., 1990; Booth and Hallet, 1993). The abundance of sediment blanketing the Puget Lowland coupled with dense vegetation and the expansive marine waters of Puget Sound, make geologic interpretations of buried crustal structures difficult without the aid of land and marine seismic methods, remote sensing technology, and drill hole data.

The enigmatic "Hood Canal-Discovery Bay fault zone" is depicted as a northeast trending, ~75 km-long, continuous fault line beginning north of Hoodsport and following Hood Canal's shoreline north before curving north-northwest through the head of Dabob Bay (Figure 1) and continuing onshore into Discovery Bay (Johnson et al., 1996). Cascadia subduction zone studies have proposed that strike-slip fault displacement affecting large regions of the forearc, may accompany and/or follow large subduction earthquakes (Wang et al., 1995). Consequently, it is important to further define the specific type and lateral extent of faulting patterns in Hood Canal. Combining this information with known sediment thickness allows a quantifiable estimate of the areas seismic potential (i.e., relative resistance to seismic shaking) to be made. Although varying in success, some efforts have been made to address this issue. Dane et al. (1965) used gravity and earthquake data to propose that Hood Canal was a "...major active fault..." separating Puget Sound from the Olympics. Marine seismic reflection lines run through northern Hood Canal and southern Dabob Bay were used along with drill hole data to generate sediment thickness contours along sections of Hood Canal's western shoreline (Yount et al., 1985). A seismic reflection line run across the south end of Toandos Peninsula by Harding et al. (1988a) underwent preliminary post-processing and was later published as a USGS Open File Report (Harding et al., 1988b). This report included a crude interpretation of faulted Tertiary bedrock with ~350 m of apparent vertical offset. Gower et al. (1985), Johnson et al. (1994), and others have suggested that the southernmost strand of the east-west trending Seattle fault, shown terminating ~10 km east of Hood Canal, may continue west and be truncated by the Hood Canal fault. Most recently, Pratt et al. (1997) depict Hood Canal as a right-lateral strike-slip fault that forms the western border of their 14 to 20 km-deep, south-dipping Puget Lowland "thrust sheet" model.

The purpose of this study is to interpret the shallow (<0.7 km) seismic character of the Hood Canal-Discovery Bay fault zone. The data set consists of approximately 100 km of single-channel, high-resolution airgun seismic data collected on April 4–5, 1994 onboard the University of Washington's *RV Thomas G. Thompson*. Particular emphasis is placed on defining Hood Canal and southern Dabob Bay's Holocene and late Pleistocene sediment thickness patterns, recognizable fault structures, and crustal deformation possibly related to the Seattle fault zone.

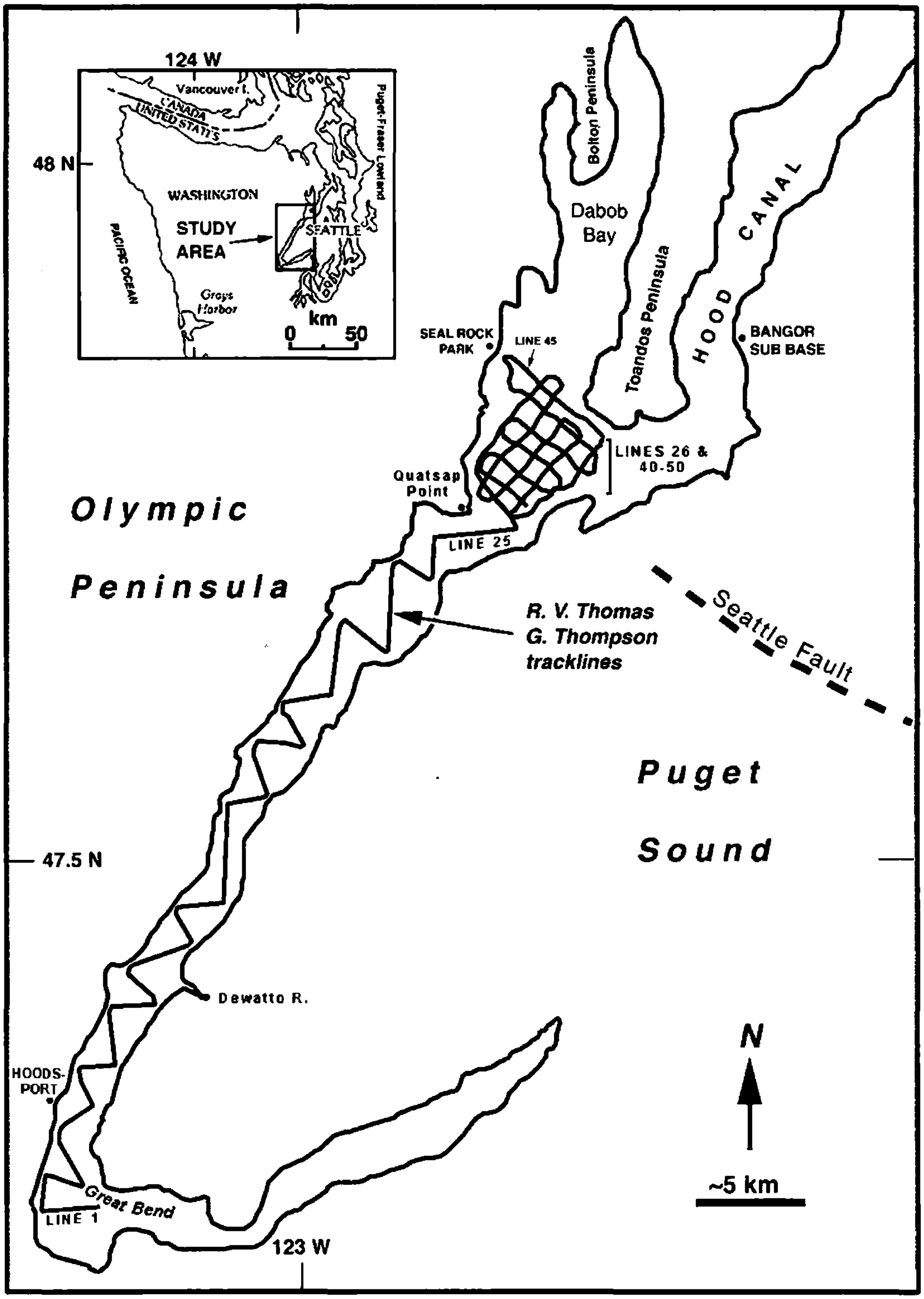

Figure1. Hood Canal study area.

Regional Geology

The Puget Lowland is located approximately 230 km east of the active Cascadia subduction zone. It lies within a broad forearc basin that extends south from the Fraser Lowland-Georgia Depression of British Columbia to Oregon's Willamette Basin. Bordering the lowland to the west is Paleocene to late Eocene rocks of the Coast Range Volcanic Province (CRVP). To the east are Mesozoic and Paleozoic terranes of the active Cascade Range. In western Washington's Olympic Mountains, basalt flow sequences of the 62–48 million year-old (Ma) Crescent Formation reach up to ~17 km in total thickness (Babcock et al., 1992). Along with the Metchosin Igneous Complex of British Columbia and Oregon's Roseburg and Siletz River Volcanics, the Crescent forms the "Coast Range basement," the earliest of three main periods of Coast Range volcanism (Snavely and MacLoed, 1974). This basement rock underlies most of western Washington and is thought to comprise a continuous crustal block that extends eastward from the Olympic Peninsula to the longitude of Seattle, Washington (Finn, 1990; Finn and Stanley, 1997). The easternmost edge of this crustal block lies concealed beneath thick glacial deposits and forms a major north-trending structural boundary separating rocks from the Coast Range and Cascade terranes. It is approximately located by juxtaposing fault lines of the north-northwest trending Coast Range Boundary and Southern Whidbey Island faults (Johnson et al., 1996).

The Olympic Accretionary Complex

Rocks of the Olympic Peninsula cover ~15,000 km^2 of northwestern Washington and form a crude triangle bordered by the Pacific to the west, Hood Canal to the east, and the Strait of Juan de Fuca to the north. The peninsula has two major geologic terranes, the "core" and "peripheral" rocks (Tabor and Cady, 1978). The core rocks include Eocene to Miocene marine sedimentary rocks with minor interbeds of pillow basalt, some of which are metamorphosed to prehnite-pumpellyite and greenschist facies (Babcock et al., 1992). For at least the last 40 million years (m.y.) (Wang et. al., 1995) the mountainous Olympic core rocks have been subjected to accretionary prism-style deformation; a result of underthrusting by the Juan de Fuca plate beneath North America. Making up the horseshoe-shaped belt of peripheral rocks are thick sequences of east-dipping Crescent basalt overlain on the north, east, and south by upper Eocene to Pliocene marine sedimentary rocks. The Crescent basalt that lines much of Hood Canal's western shoreline is a mechanically strong lithologic unit. This is indicated by its lack of seismicity (Dewberry, 1996), great thickness, and general lack of deformational structures like those seen in the Olympic core rocks. However, during accretion of the core rocks, this rigid basalt mass likely developed compensating fault structures (e.g., "tear faults"). Final isostatic uplift of the Olympic Peninsula at about 17 Ma resulted in the present structural orientation of the east-dipping to near-vertical Crescent basalt flow sequences (Tabor and Cady, 1978).

Quaternary Glaciation

Cordilleran Ice Sheet advances into western Washington occurred at least five times during the late Quaternary (Thorson, 1996). Fed by alpine glaciers in the Canadian Coast Range, the tidewater "Juan de Fuca lobe" advanced westward into the Strait of Georgia and eventually southward into the Puget Lowland as the "Puget lobe". Ice completely filled the Puget Lowland between the Olympic Mountains and Cascade Range. Following the most recent Fraser glaciation maximum (~15 thousand years ago [ka]), deglaciation of the Juan de Fuca-Puget lobe system was rapid and complete by ~13.5 ka, leaving behind an extensive low-gradient outwash plain termed the "great lowland fill" (Booth, 1994). Following deglaciation was an intense, but relatively brief period of isostatic uplift-induced crustal seismicity (Thorson, 1996). The primary source of this seismicity were crustal blocks located along pre-existing structural discontinuities, particularly those oriented perpendicular to ice flow directions and parallel to ice margins (Thorson, 1996). Present-day Hood Canal, oriented parallel and just up-glacier from the former Puget ice lobe's western margin, would have been ideally suited for the maximum expression of postglacial faulting (Thorson, 1996).

Puget Lowland Seismicity

Today, the central and northern Puget Lowland displays two general zones of seismicity (Symons and Crosson, 1997). The first, a diffuse zone within the North American plate and above ~35 km; and the second, a deeper zone (~40–70 km) within the obliquely subducting (rate of ~40 mm/yr; N68_E direction; Savage et al., 1991) Juan de Fuca plate. Beneath Puget Sound, crustal earthquake epicenters are generally confined to the glaciated area with a strong correlation between earthquake depth and glacial loading (Thorson, 1996). Noting paleoseismic evidence for Holocene displacement on the Seattle fault, Thorson (1996) suggests this correlation may represent a return to a pre-glacial "background" and more seismically active regional tectonic setting, a setting in which the transfer of subduction zone stresses in the forearc is not modulated or stabilized by glacial loading. Aprea et al. (1998) showed that crustal seismicity occurs only within the Crescent Formation basalt underlying the Seattle basin. They suggest that thick (>30 km) Crescent volcanics may effectively prevent the subduction of Olympic core rocks and help explain the concentration of crustal earthquakes beneath the Puget Lowland.

Local Geology

Detailed geologic mapping along the west and north-northeast shoreline of Hood Canal was done by Carson (1976a, 1976b) and Birdseye (1976). To date, no detailed geologic maps are available for the eastern shoreline of Hood Canal. The western side of Hood Canal dominantly comprises upper to lower Eocene basalt, interbedded conglomerate, and minor sedimentary deposits of the Crescent Formation. Outcrops of dark brown, columnar and massive Crescent basalt with flow tops dipping east at angles of ~10_–35_ are especially common along the mid-to-northern shoreline (Carson, 1976a, 1976b). However, basalt flows in the Dosewallips River valley, which drains into western Hood Canal, are oriented "...near vertical with tops facing east" (Babcock et al., 1992).

Overlying the Crescent is Oligocene (?) Twin River Formation volcanoclastics and pre-Fraser deposits of Olympia and Puget lobe glacial tills and outwash along with non-glacial sediments. Variably thick layers of Pleistocene Fraser glaciation sand and gravel tills, proglacial lacustrine silt, sand, clays, glacial drift, and outwash deposits are found throughout the area. Exposed Holocene deposits include alluvial fan sands and gravels, and older deglaciation to younger (<50-year-old) landslide deposits (Carson, 1976a, 1976b). The Toandos Peninsula (Figure 1) forms the eastern shoreline of Dabob Bay and is covered by thick Fraser advance outwash and lodgement tills with no mapped outcrops of Crescent basalt (Birdseye, 1976).

Seattle and Saddle Mountain East Faults

Both the Seattle and Saddle Mountain East faults show either direct or paleoseismic evidence for late Quaternary movement (e.g., Wilson et al., 1979; Johnson et al., 1996). The Seattle fault zone consists of four south-dipping, generally east-west trending fault segments with dominantly reverse or thrust displacement (Johnson et al., 1994). Throughout the Quaternary and possibly much of the Tertiary periods, fault strands of the Seattle fault zone have been subject to extensive fault displacement. Most notably, a ~7 m vertical offset along strand two of the Seattle fault which triggered a strong earthquake 1100 yrs ago (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992; Karlin and Abella, 1996; Schuster et al., 1992). The Saddle Mountain East fault is located ~5 km west of Hood Canal's Lilliwaup Creek. This 1.8 km-long fault scarp parallels Hood Canal, strikes N22_E, dips at 75_ to the SE, and exhibits 3.5 m of reverse dip-slip displacement dated at ~1,155 years ago and possibly coeval with displacement along the Seattle fault zone (Wilson et al., 1979). It is one of several crustal faults in this area thought to have developed during complex faulting and doming of the Olympic Peninsula.

Methods

The ~100 km of seismic track lines are shown in Figure 1. Trackline turn angles were limited to 50° to avoid difficult ship maneuvers, minimize hydrophone streamer drift, and facilitate smooth transition between adjoining track lines. NAVSTAR Global Positioning System (GPS) fixes, with an estimated positional accuracy of ± 50 m, were recorded and tagged on the seismic records at one minute intervals resulting in ~8.0 positional fixes/km. Water depth (accuracy of 1.0% water depth) and 3.5 kHz sub-bottom bathymetry were continually recorded. The ship's speed was maintained at <4.5 knots throughout the survey.

The sound source was a single 655 cm^3 (40 in^3) Bolt PAR 600B air-gun with an inlet pressure of 124 bar (~1800 psi), firing at a 2.2 second interval, and towed 70 m directly aft of *RV Thomas G. Thompson*. An AQ-1 titanate-zirconate, 200-element streamer (15 cm-spacing) was deployed from a four m-long boom extending off the ship's port quarter. The airgun was maintained at a tow depth of about 6 m and the streamer at approximately five m. The low and high band streamer signals (30–90 and 40–120 Hz) were routed through 30 dB amplifiers and displayed on separate channels of an EPC 9600 digital thermal graphic recorder (one and two sec sweeps). Digital audiotape (DAT) was used to record the raw acoustic, trigger signal, and amplifier data.

Data set post-processing took place over a four-day period at the University of Washington, Seattle with Dr. Thomas L. Pratt (USGS). Raw DAT tapes were played back with a TEAC DAT recorder, re-formatted from tape analog to digital format, and then re-digitized into seg-y format (2000 samples/sec) using the USGS data acquisition software program "MUDSEIS." The data set was then band-pass filtered at 10, 20, 160, and 320 Hz, deconvolved, gained (amplitude-balanced), migrated, and displayed as Postscript files using a UNIX-based workstation. After processing, Geologic structures observed in the records were line-drawn using graphics software. Seismic stratigraphic unit contacts were correlated using a scaled fence diagram. Additionally, a detailed bathymetry data set (~130 data points/km^2) covering mid-to-southern Hood Canal was obtained from the NOAA facility at Sand Point, Washington.

Results

Due to space and size limitations only two seismic profiles are included along with both an isopach map and inferred fault map for tracklines 40–50 (see Figure 1). For reference when viewing Figures 2 and 3, "M1" and "M2" designate first and second reflection multiples; "Qh" denotes Quaternary and Holocene glacial-marine sediments; and "Cr" refers to Crescent Formation bedrock (see text for description).

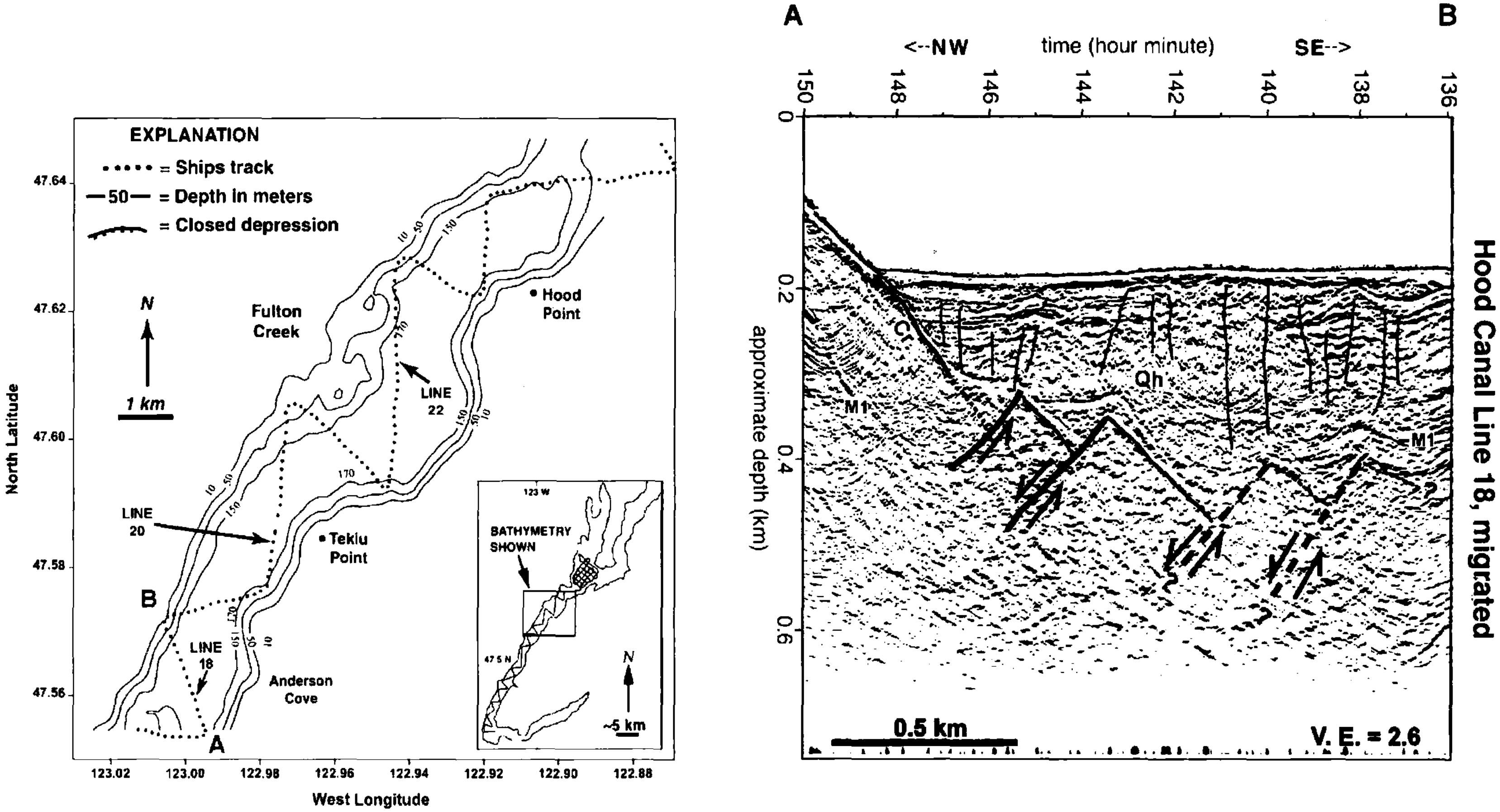

Figure 2. Interpreted seismic profile, trackline 18. This profile crosses Hood Canal beginning on the east shoreline (approx. latitude of Cummings Point) and ends on the western shoreline directly across from Anderson Cove (see "line 18," Figure 1). A ~20–50 m-thick, well-stratified, parallel reflector caps ~250 m of acoustically discontinuous and unstratified glacial sediment. Obvious normal faulting is observed in the steeply east-dipping Crescent basalt unit. The "hard reflector" filling and draping the fault block "V's" may be a compact basal till. The current fault block orientation may reflect a strike-slip or thrust fault stress component. Fault planes are dashed where unclear. Upward propagating faults within the sediment fill are indicated. Additionally, a pressure-ridge structure may be visible close to the surface layer (upper right, Figure 2). This type of compressional feature typically forms between multiple fault traces of strike-slip fault zones.

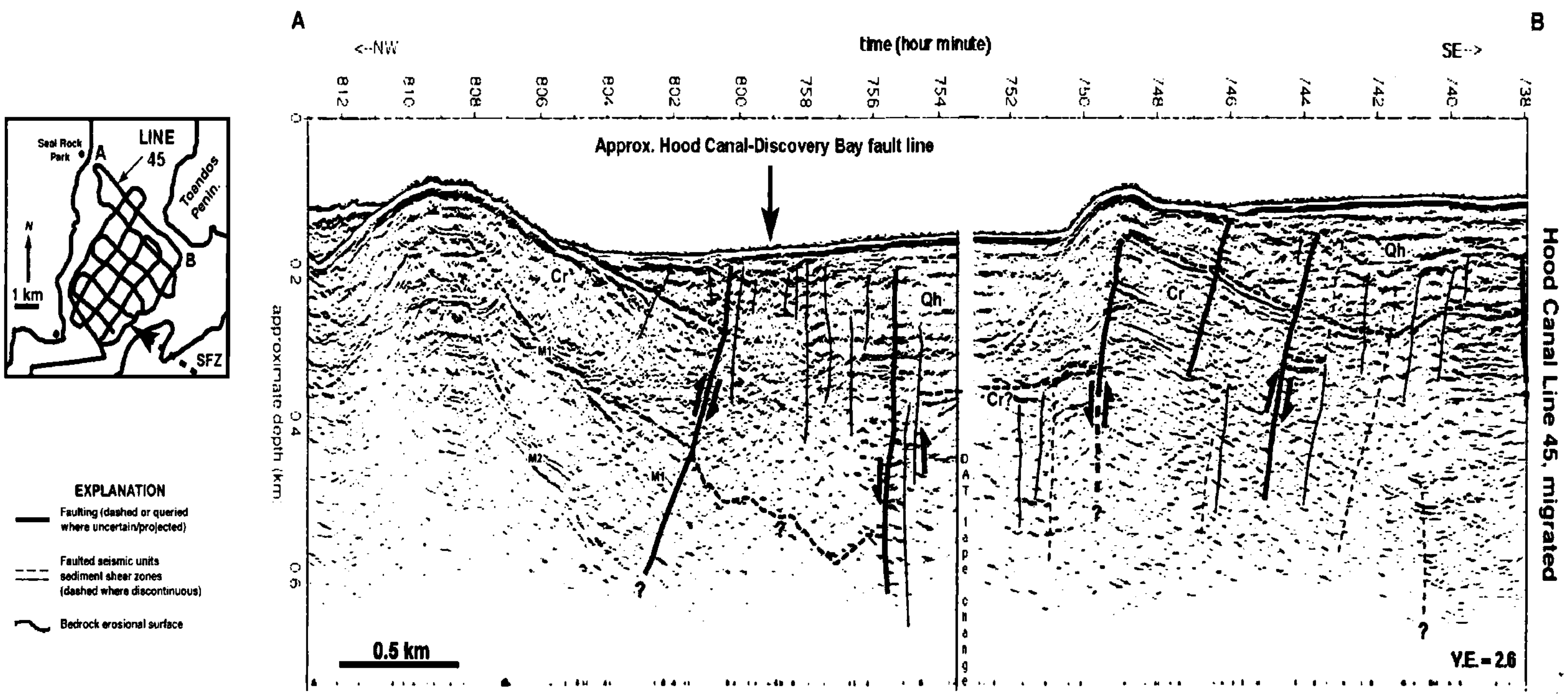

Figure 3. Interpreted Seismic profile, Line 45. This ~4 km-long profile starts SW of Oak Head, crosses Dabob Bay and ends ~1 km SE of Seal Rock beach (see "line 45," Figure 1). An asymmetric V-shaped valley can be seen in Dabob Bay infilled with 200 to 350 m of acoustically unstratified to weakly stratified Quaternary sediments. A 10–30 m-thick well-stratified surface layer overlies the basin fill. To the extreme upper left of Figure 3, east-dipping Crescent basalt can be traced ~1 km beneath the sediments where it is abruptly truncated. This faulted bedrock corresponds nicely with the Gower et al. (1985) fault trace. A deep sediment-filled graben structure occupies the center of Dabob Bay. Along the eastern side of Dabob Bay, uplifted and/or rotated Crescent blocks are draped by glacial landslide deposits from Toandos Peninsula. The peninsula's western shoreline may continue NE along defined by the upper edge of this rotated crustal block (?). Blind faults terminate within 50 m of the surface layer and sediment deformation features are pervasive beneath central Dabob Bay. Movement along bedrock fault planes below these sediments may have initiated these blind faults.

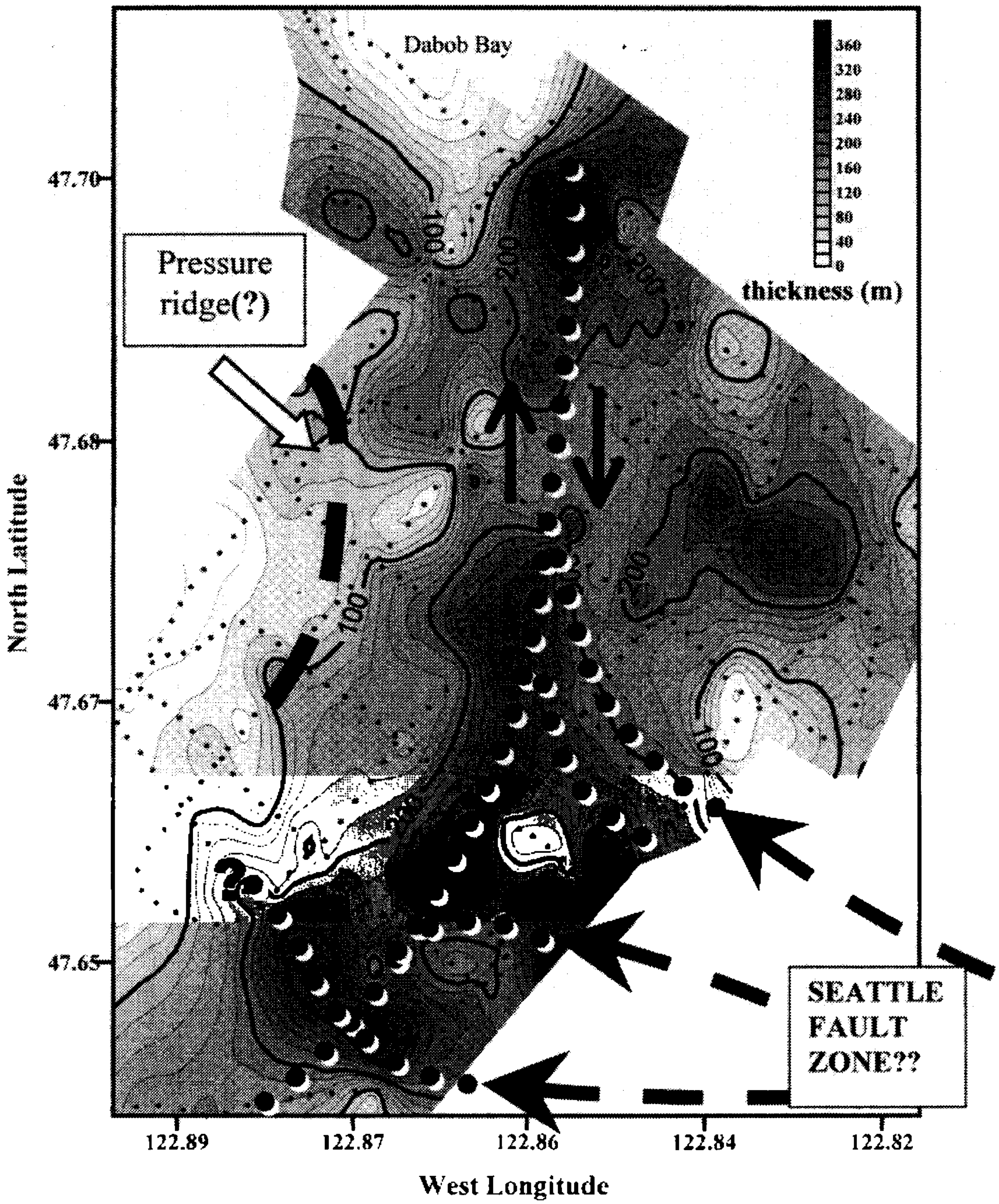

Figure 4. Isopach (sediment-thickness) map. This map details the thickness (in meters) of Quaternary sediment covering the faulted Crescent basalt over an approximate 25 km^2 area between Seal rock to the north and Quatsop Point to the south. The sediment cover generally thickens eastward varying from 0 to ~350 m. Toward the middle of the Hood Canal trough, the thicker sediment packets (>200 m) fill down-dropped crustal blocks trending very close to the Gower et al. (1985) fault trace. The northwest-trending closed contour sausage-shaped feature (~47.65N, 122.87W) may be a faulted zone crossing Hood Canal. The 380 m contour at the head of Dabob Bay represents the NE-trending graben structure noted on Figure 5 (trackline 45).

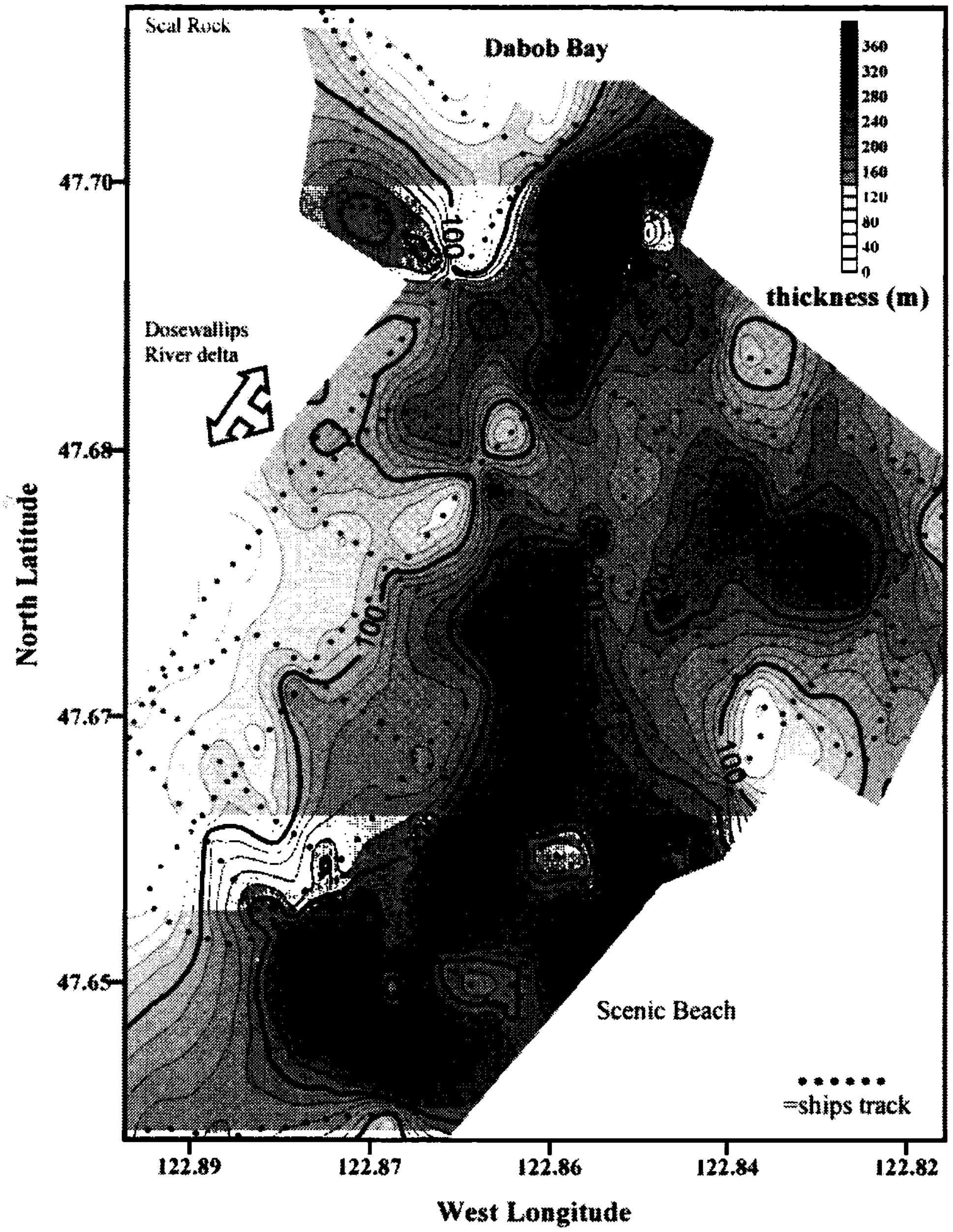

Figure 5. Interpreted fault map overlaid on Figure 4. This preliminary map shows a few of the many possible fault splay patterns joining the Hood Canal-Discovery Bay fault zone. The mapped pressure ridge structure was noted on four separate seismic profiles (none of which are shown in this report) and may be a segmented or en echelon structure. These are quite common with left bending or left-stepping dextral fault zones.

Conclusions

1. There is geophysical evidence for normal and strike-slip faulting in the Hood Canal and southern Dabob Bay area. This faulting pattern is generally consistent with the Gower et al. (1985) fault trace.

2. Quaternary sediment thickness in the ~25 km^2 mapped area varies from 0 to 380 m, with a general increase in thickness east and toward the canal centerline.
3. Blind faults terminating <30 m below the sediment/water interface may be co-seismic in nature; possibly related to displacement along the Seattle fault zone.
4. Fault splays of the Seattle fault zone may be present in Hood Canal and play a role in the development of anomalous isopach contours, pressure ridge structures, and sediment deformational patterns seen in Hood Canal.

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Observation of an Intense Deep-Water Intrusion in Puget Sound

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Introduction

Bottom water intrusions are one of the major circulation features of Puget Sound (Cannon et al., 1990) and are a major source of sub-tidal variability (Bretschneider et al., 1985). Together with tidal pumping at the Narrows, intrusions are responsible for the short residence time of water within the main basin and are crucial to removal of contaminants. Deep-water intrusions are formed during neap tides when the mixing over the Admiralty Inlet sill is at a minimum. The water formed during neap tides replaces the resident deep water within the main basin. When tidal mixing over the sills is more intense, intermediate water intrusions may occur with the formation of an advectively forced, step-like density structure within the main basin.

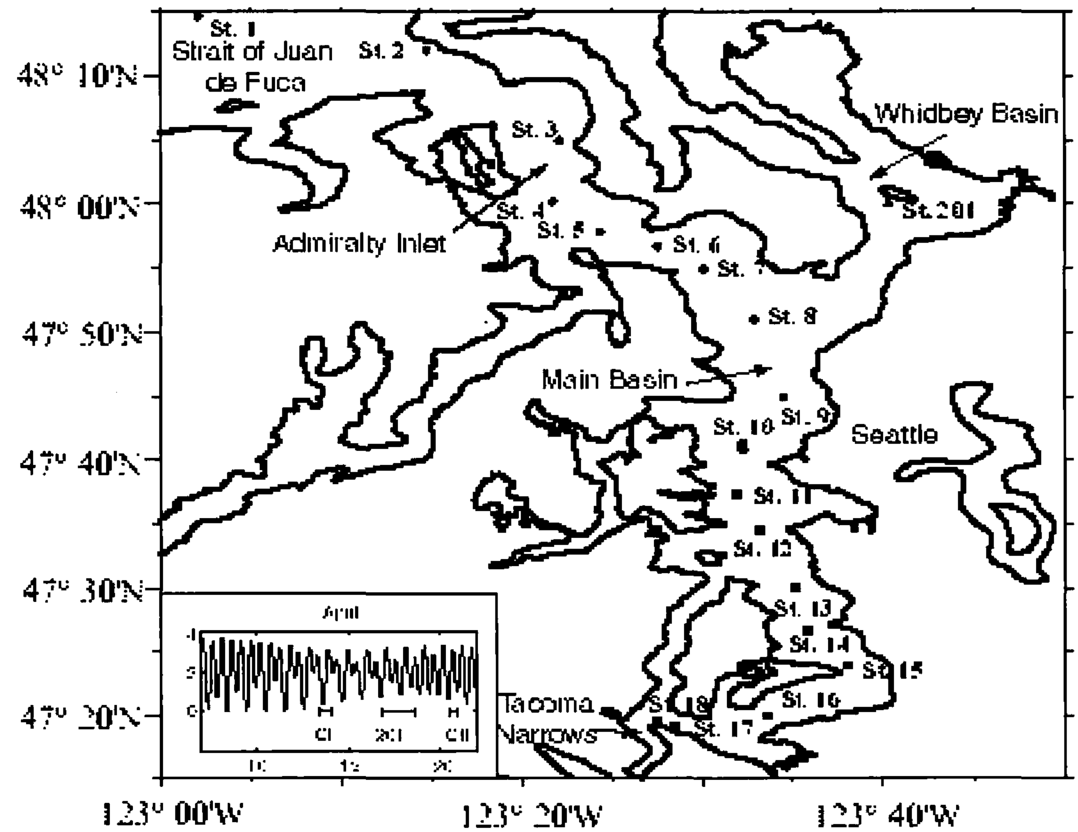


Figure 1. Map of Puget Sound with location of stations and Seattle tides during the study. Stations 1 to 10 were occupied during the intrusions on 13–14 April 1997 (section C-1); stations 10 to 18 were occupied one week after the intrusion on 20 April 1997 (C-11). Station 201 was occupied on 17 April 1997.

The dynamics of chlorophyll *a* (chl *a*) at depth in Puget Sound have been linked to bottom water intrusions by Winter et al. (1975), who observed increased pigment concentrations associated with increased salinity. They argued that sinking could not account for their observations. During our cruises in April 1997 we observed the transport of waters with high chl *a* concentration to depth and the disappearance of pigments within these waters.

Here we present observations from two hydrographic sections in April, 1997; the first section took place during an intense neap tide intrusion over the Admiralty Inlet sill region and the second section was performed a week later within the main basin.

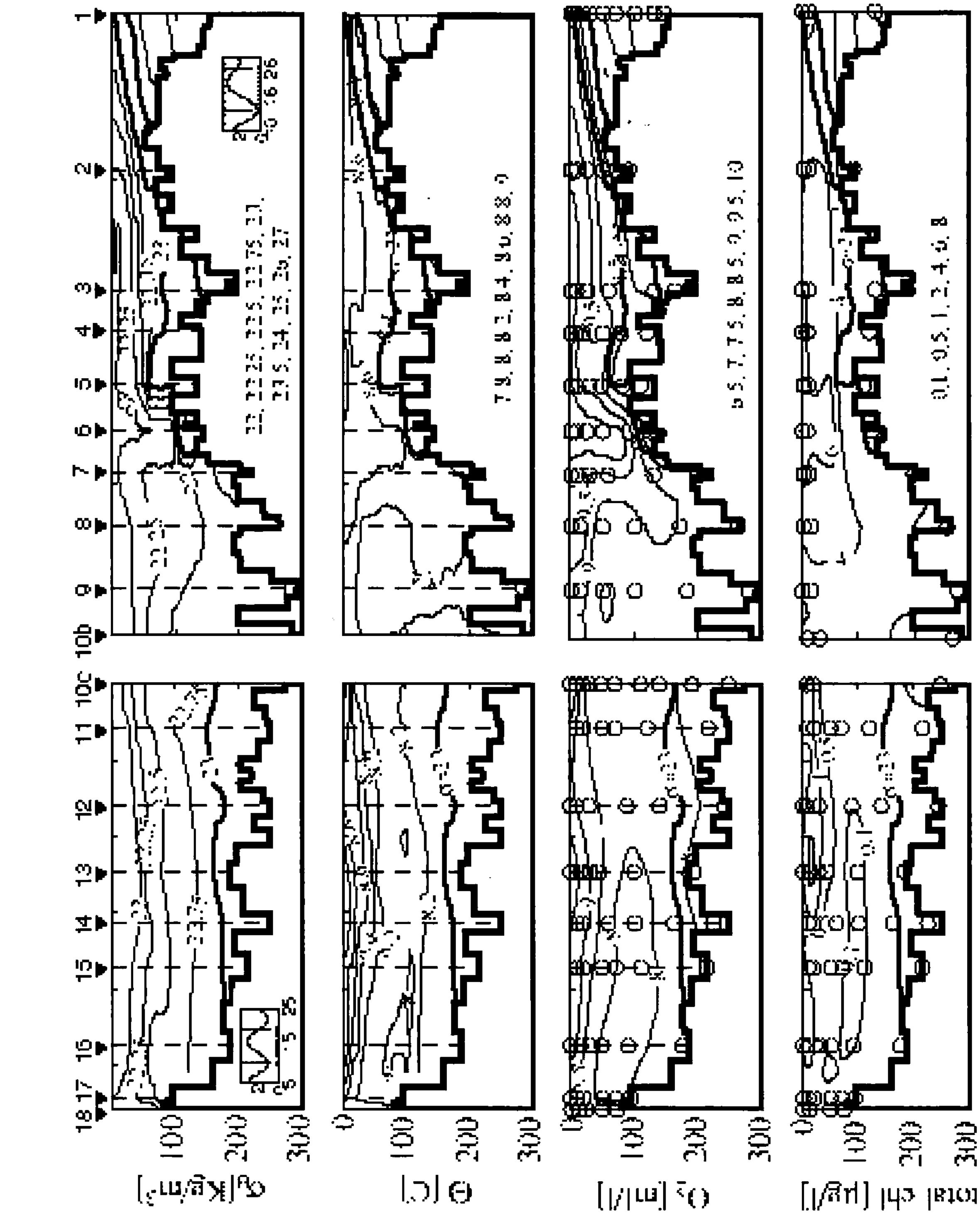
Methods

Hydrographic data were collected during two survey sections conducted *aboard R/V Clifford A. Barnes* on 13–14 (C-I) and 20 (C-II) April 1997. Hydrographic casts were performed at 18 stations (Figure 1); additional casts were taken at Station (St.) 10, i.e., at the beginning and end of each of the two sections. The first cruise was planned to coincide with the neap tide intrusion at Admiralty Inlet (Figure 1), while the second one was intended to determine how far the deep-water intrusion propagated through the main basin during a one-week period. Additional hydrographic measurements were taken in between our two sections during a University of Washington student cruise to Whidbey Basin (St. 201, Figure 1).

The sampling design (Figure 1) followed the deepest route through the main basin and included the deep holes in the bathymetry where the densest water was expected to be found. The hydrographic sections were performed from north to south and occurred mostly during flood tides (Figure 1). Station 10a was visited before section C-I was started to provide a reference for conditions prior to the intrusion. Station 10 was revisited at the end of C-I (as St. 10b) and twice during C-II (as Sts. 10c and 10d) to estimate variability at one station.

Conductivity, temperature and pressure were measured with a SBE-11 CTD; a Sea-Tech transmissometer (25-cm path length) was used to measure light transmittance in the water. The CTD was lowered to within less than 10 m off the bottom. Water samples were collected using 12 5-L Niskin bottles mounted on a rosette sampler. Discrete samples were analyzed for oxygen (Winkler titration), chl *a* and pheopigment concentrations (Holm-Hansen et al., 1965). In addition, samples for chl *a* and pheopigment concentrations associated with particles larger than 70 m were also collected at discrete depths. Water was filtered through 70 µm Nitex filters. The filters were analyzed for pigment concentrations and the filtrates were frozen in liquid nitrogen for flow cytometric analysis in the shore-based laboratory.

The hydrographic data (Figure 2) were plotted using an objective analysis mapping technique (Roemmich, 1983). The strength of this method is that it generates a contour map that provides the best fit to the data, given a user-determined error estimate and correlation function, and also generates an error map. These features are important when sparse, unequally spaced data are plotted, such as chl *a* concentrations from discrete water samples. For the continuous-profile CTD data, a correlation function was chosen to be Gaussian with a horizontal correlation e-folding length of one station and a vertical correlation e-folding length of 5 m. For the discrete samples, a variable vertical correlation was used that varied linearly from 10 m near the surface to 80 m at 250 m depth. The average value of properties within the intrusion were calculated using the interpolated fields derived from the objective analysis method, with the constraint that the relative error be less than 30%.



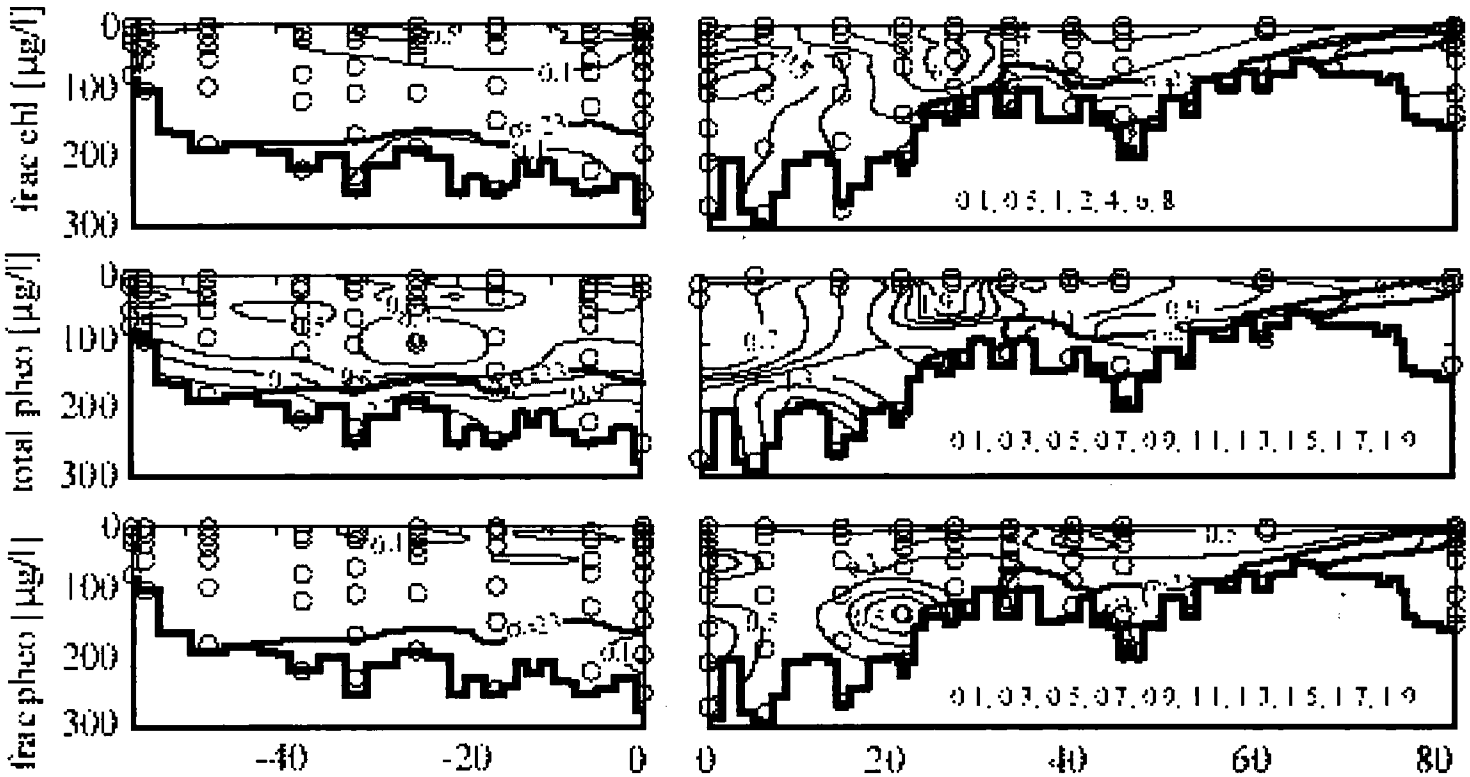


Figure 2. Density (σ_θ), potential temperature (θ), oxygen (O_2), total chl a (chlorophyll a), frac chl a (chl a associated with particles > 70μ), total pheopigment (pheo), and frac pheo (pheo associated with particles > 70μ) during the two sections. Insets contain the contours used for each plot. Bold lines represent the isopycnal that defines the deep water intrusion (σ_θ=23-23.5).

Flow cytometric analyses were performed on an EPICS Profile flow cytometer. In general the low concentration of particles observed (i.e., a few hundred particles per 200 ml) precluded statistical analysis of dynamics of changes in particle fluorescence characteristics (the error bars were larger than the changes in the signal). However, three different groups of particles were classified according to their fluorescence and scattering properties (Figure 3). The classification was computed using an objective method developed in our lab (Boss and Perry, unpublished); clusters of particle were differentiated by unique combinations of red and orange fluorescence and forward scatter.

Comparisons with laboratory cultures of two strains of *Synechococcus* sp. show that the F1 and F2 particle groups are similar in fluorescence and scattering patterns to *S. bacillaris* (clone SYNG) and *Synechococcus* WH7803 (clone SYNDC2), respectively a coastal and a pelagic cyanobacterium (Olson et al., 1988). Group F3 had fluorescence characteristics similar to F2 but with much greater forward scatter, presumably due to larger size. The identity of the F3 group is unknown, but these particles could potentially be fragments of fecal material, egested cells or autotrophic dinoflagellates.

To assess the degree to which dilution controlled the changes in particle concentration, 20-L water samples were taken from 10 m at both St. 10b and St. 1 and from the bottom at St. 9. The water samples were stored at 8° C room in the dark and were subsampled during the week between the cruises to provide a reference for changes observed in the intrusion waters during section C-II.

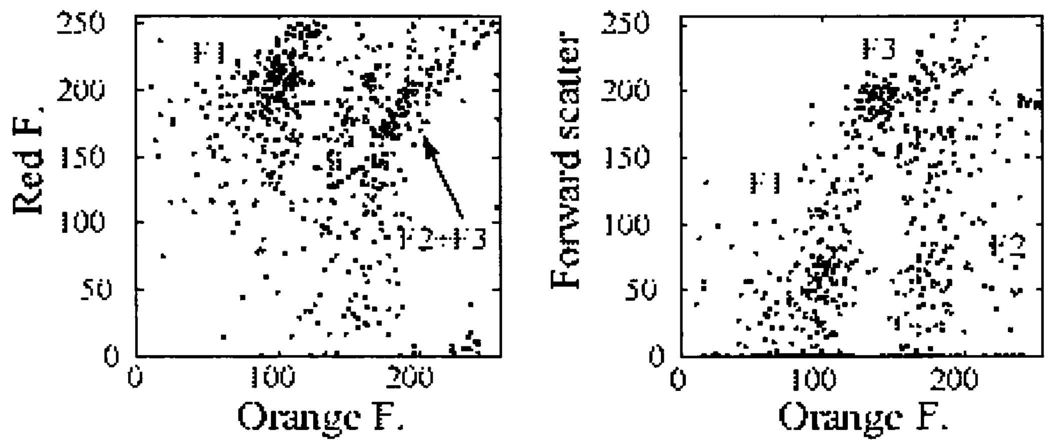


Figure 3. Flow cytometeric analysis of bottom water from St. 16. Three classes of particles are distinguished based on chlorophyll *a* fluorescence (Red F.) and forward scatter (an indication of particle size). The F1 particles are uniquely distinguished by their lower orange fluorescence, while the F2 and F3 particles are distinguished based on differences in forward scatter. The distribution of each group within the water column is shown in Figure 6.

Observations

Hydrography

During the C-I section a strong front was observed between Sts. 5 and 6 (right panels, Figure 2). This front was associated with the intense downwelling that resulted from the interaction of flow and inlet topography. A similar feature was observed at the same location in the high-resolution measurements made by Turner and Gregg (1995). Two intrusive water masses were characterized during the C-I section: one to the north and one to the south of the front. The water mass to the south ($\sigma_\theta \sim 22.75$) had θ-S properties (Figure 4) and high oxygen and pigment concentrations indicative of a mixture of surface Puget Sound waters and oceanic waters. The temperature, pigment, and particularly the oxygen contours in Figure 2 all indicate that this water mass was intruding, at depth, into the main basin. We refer to this water mass as the first intrusion.

To the north of the front, a tongue of dense ($23.2 > \sigma_\theta > 22.9$) water could be observed at the bottom at St. 7 and could be traced (with sloping isopycnals) to the surface in the Straits (St. 1). This

water mass had similar properties to those observed in the bottom of the main basin during the second cruise; hence, we refer to this dense water as the source of the deep-water intrusion.

Water properties in the bottom of Puget Sound at St. 10 (Figure 5) indicate that by the end of the first section (10b) a warmer water mass had penetrated below 180m. A closer look reveals the existence of two maximums in temperature (one at 180 m and a second at the bottom). These data are suggestive of two separate intrusive features that can also be observed in the θ-S properties at St. 9 (Figure 4). Each intrusive water mass was formed by a different mixture of oceanic and Puget Sound water, with the density determined by the proportion of each in the admixture.

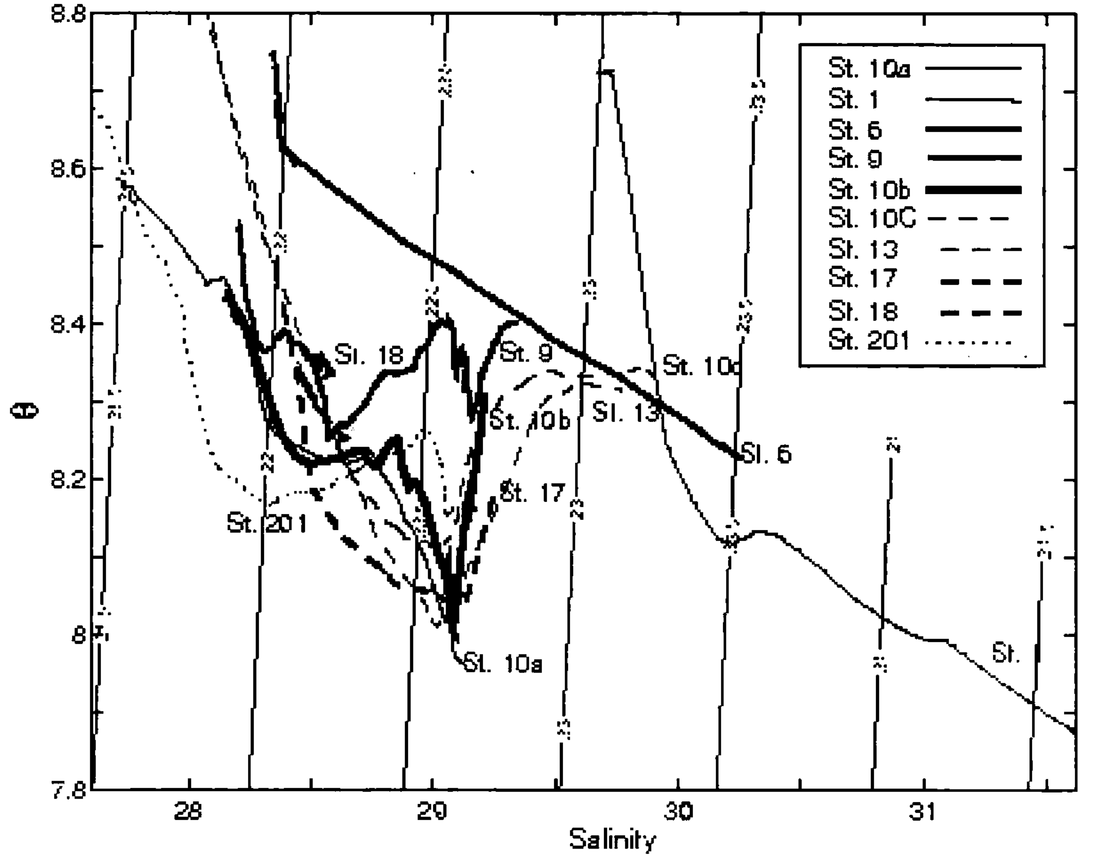


Figure 4. Potential temperature (θ)-salinity diagram of representative stations from both hydrographic sections with overlain density (σ_θ) contours. The source of the bottom waters (σ_θ>23) can be traced to St. 1. The water resident in the main basin water prior to the intrusion (bottom of St. 10a) was lifted higher into the water column by the intrusion (St. 10c). The influence of Whidbey Basin waters (St. 201) can be observed closer to the surface (e.g., St. 10b for $\sigma_\theta \approx 22.25$).

Data from the C-II section, taken one week later, are shown in the left panels of Figure 2. The water below ~170 m had the same θ-S properties as the dense deep-water intrusion in the C-I section. The volume of water below 170 m in the main basin of Puget Sound was approximately 7 km^3 (based on the 300 m resolution, bathymetric data base compiled by Dr. Miles Logsdon, University of Washington). We used a simple mass balance to calculate the horizontal length of the intrusion, based on an estimated width for Admiralty Inlet of ~7 km and a vertical scale for the deep-water intrusion of ~50 m (Figure 2). We estimated that the length of the intruding water mass should be approximately 20 km. Because the distance between Sts. 1 and 7 is about 30 km, we believe that our first hydrographic section captured the bulk of the waters that penetrated below 170 m into Puget Sound. The conservation of θ-S properties in

the intrusion indicates that this dense water penetrated with little mixing. These results are consistent with the notion that during neap tides mixing and modification of intruding oceanic waters are minimal.

The θ-S properties at depth at St. 201 in Whidbey Basin show a similar intrusive tongue as that observed at St. 9 during C-I (yet somewhat mixed with Puget Sound intermediate water, Figure 4) implying that the first intrusion penetrated into the Whidbey basin. The θ-S properties at the entrance of the Tacoma Narrows (St. 18) indicate that water there was upwelled from intermediate depths in the main basin (~100 m, Figure 2). Note that the water that resided at depth prior to the intrusion (bottom of St. 10a) was at about 70 m during C-II (Figures 4–5), uplifted by the deep intrusion and subsequent intermediate ones.

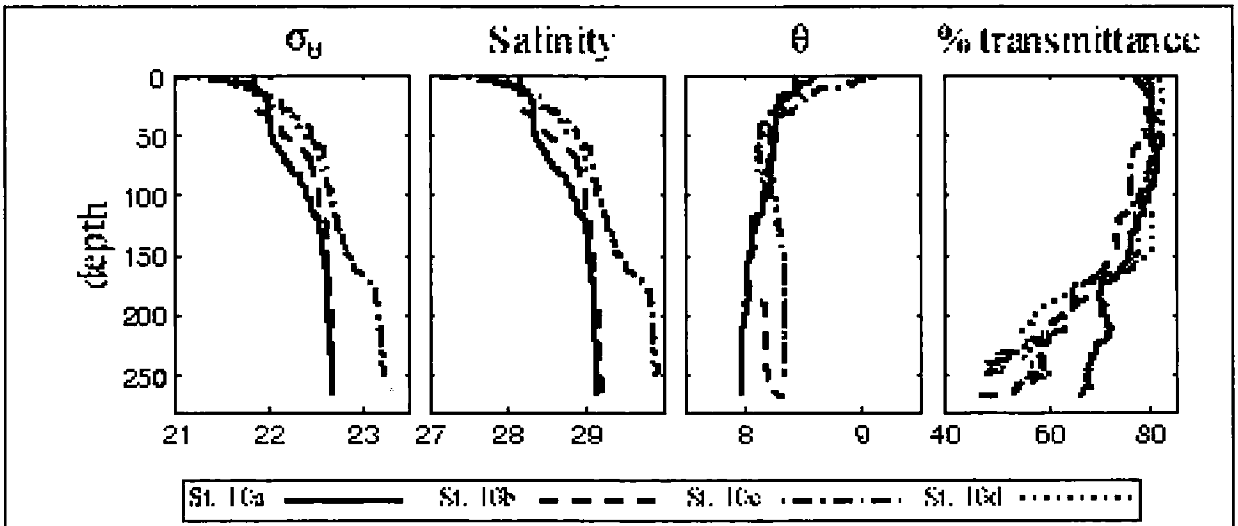


Figure 5. Density (σ_θ), salinity, potential temperature (θ), percent (%) light transmittance at St. 10 before (St. 10a) and after bottom intrusions entered Puget Sound (St. 10 b, c, and d).

Table 1. Average water properties within the deep-water intrusion (23.2 > σ_θ> 22.9), and standard deviations, based on interpolation by objective analysis (see Figure 2 for symbols and units). St. 10a water properties at 202 m, measured prior to the intrusion, are given for reference.

	σ_θ	θ	O_2	Chl *a*	Chl *a* >70μ	Pheo	Pheo >70μ
Section-I	23 (0.1)	8.45 (0.01)	8.6 (0.3)	2.3 (0.4)	0.9 (0.2)	0.9 (0.3)	0.16 (0.1)
Section-II	23 (0.1)	8.32 (0.01)	8 (0.1)	0.4 (0.1)	0.1 (0.05)	0.9 (0.4)	0.02 (0.02)
10a (202 m)	22.6	8	7.98	0.24 (.02)	0.03	0.42 (.05)	0.07

Biologically Active Tracers

A phytoplankton bloom ([chl *a*] > 8 mg/m^3) occurred at Sts. 5 and 6 during the C-I section. Downwelling of water with high chl *a* concentration was observed to 100m depth with subsequent entrainment into intermediate waters (Figure 2). About 80% of the chl *a* concentration in the downwelling water was associated with the fraction of cells larger than 70 m; these data suggest that the bloom was due to large cells or chain-forming diatoms (diatom chains were found in water a sample collected from the surface at St. 1, S. Menden-Deuer, personal communication). In the water comprising the deep-water intrusion only 40% of the chl *a* was associated with cells larger than 70 m (Table 1), indicating that the waters in the Straits of Juan de Fuca contained relatively more small cells than the surface waters of Puget Sound. In

contrast a higher proportion of pheopigments, degradation products of chl *a* formed during zooplankton grazing of phytoplankton, were found in the size fraction smaller than 70 m. These findings could be indicative of high grazing rates by small zooplankton. Small dinoflagellates (*Protoperidinium sp.*) that feed on large diatom chains were observed in a water sample collected from the surface waters at St. 1 (S. Menden-Deuer, personal communication). Another possibility is that pellets of larger zooplankton (~300 m copepods, B. Frost, personal communication) break within the water column or during filtration. Buck and Newton (1995) found in Dabob Bay, Washington, that dinoflagellates were an important source of small fecal pellets. These pellets were devoid of pigments, although Strom (1993) has shown that the fecal pellets of certain dinoflagellates do contain pheopigments. Why pheopigments were more abundant in small particles, relative to chl *a*, in our samples remains an open question.

At St. 10 prior to the intrusion, concentrations of chl *a* and pheopigments near the bottowere 0.24 and 0.4 mg/m^3 respectively, much lower than concentrations within the deep intrusion (2.4 and 0.9 mg/m^3 respectively, Table 1). A week later, chl *a* concentrations within the deep-water intrusion dropped by more than 80% while pheopigments at depth had similar values to those in the intrusion tongue (~0.9 mg/m^3). The loss of chl *a* could be due both to sinking of the large cells to the bottom and to conversion of chl *a* to pheopigments through zooplankton grazing with subsequent sinking of pellets. In both hydrographic sections the bulk of the measured pheopigments were from the fraction of particles smaller than 70m. Small particles sink faster than large particles, and thus are expected to stay longer in the water column.

Oxygen concentrations within the intrusion were reduced from 8.6 to 8.0 ml/L during the week following the intrusion (Table 1). Assuming a stochiometric ratio of 1.0 mol O2 respired per 1.45 mol C oxidized and a gram ratio of C/chl *a* of 30, oxidation of the carbon associated with 2 mg/m^3 of chl *a* would result in the consumption of 0.2ml/L, about 30% of the observed reduction.

Another potential source of organic carbon is Seattle's sewage outfall, which can release up to 400 million gallons of sewage a day, with a maximum concentration of dissolved organic carbon of 30 mg/L. Assuming an extreme scenario, i.e., all the organic carbon gets oxidized within the deep water mass (i.e, an input of 1 part sewage for ~650 parts of deep water), the disappearance of only another 0.15 ml/L can be explained. In order to achieve an oxygen mass balance, we have to assume either that organic material is respired within the sediment (i.e., the sediments are a sink for the water column's oxygen) or that organic matter previously deposited on the bottom is resuspended by the intrusion and respired within the water column (indeed, low transmittance is observed near the bottom). It is interesting to note that intrusions can both import relatively oxygenated surface waters as well as the biogenic material whose degradation will consume oxygen. The contribution of surface carbon to deep waters in Puget Sound by sinking is a relatively unimportant route for carbon transport relative to advective transport by intrusion (Winter et al., 1975).

Flow cytometric analysis of the particles smaller than 70 m revealed a single group that had significantly higher concentrations near the surface (F1, similar to the coastal cyanobacteria, SYNG, Figure 3). This group also had a secondary concentration maximum associated with the intrusive waters at the bottom of the main basin during the second cruise. The distribution of the F1 particles near the Tacoma Narrows (Sts. 17 and 18) tracked the upwelling of intermediate waters into the Narrows and the mixing with waters with low concentrations of F1 particles. These data display clearly the effect of mixing at the Narrows in homogenizing water properties.

Compared with the deep-water intrusion waters during C-I, concentration of F1 particles dropped from ~600 cells/200 ml to ~300 cells/200 ml in the bottom of the main basin during C-II, due possibly to dilution, grazing and mortality. Prior to the intrusion there were 90 cells of F1 at depth. Group F2 had a small vertical gradient in comparison to F1. Its values increase ~200 near the surface and are fairly high at depth (~130). Prior to the intrusion there were 70 cells/200 ml for this group at the bottom of St. 10a. In laboratory incubations of collected samples, the concentration of particles associated with phytoplankton (F1+ F2) were found to decrease by 40–60% after a week (data not shown). Assuming that the trophic dynamics within the incubation bottles were similar to those within the deep water, these observations suggest that little dilution occurred in the intrusive water body, as observed in the hydrography. Notice that the small cyanos are better preserved than the

bulk total and fractionated chl *a* that are reduced by more than 80%.

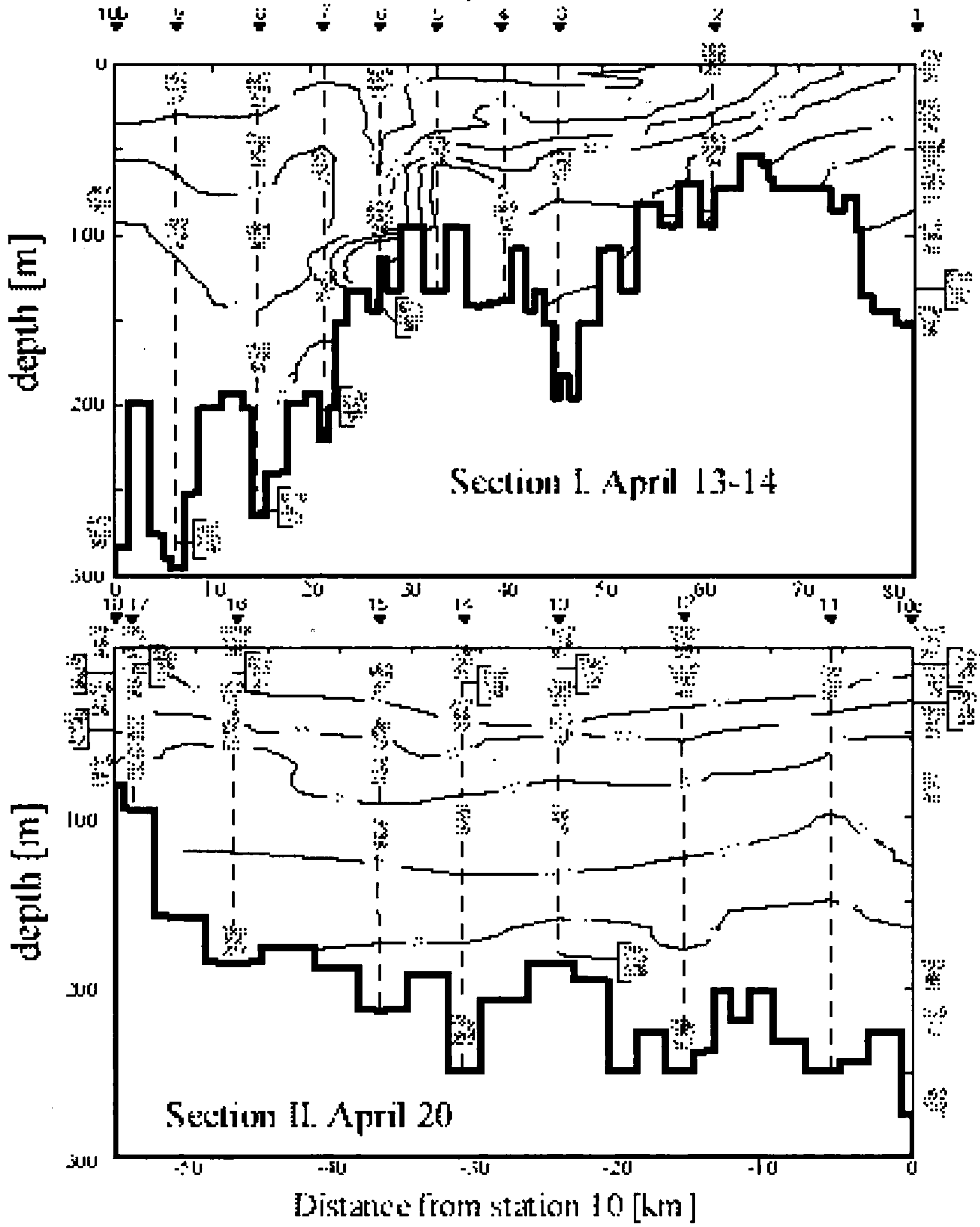


Figure 6. Distribution of three groups of particles classified from flow cytometric (see Figure 3). Concentrations of each type of particle (cell number per 200 µl) are given in a cluster of three numbers for F1 (top), F2 (middle), and F3 (lower) particle groups. Solid lines are density contours (σ_θ).

Group F3 increased near the bottom of Puget Sound, was low near the surface and did not have an apparent source except for being correlated with low optical transmittance (Figure 4, values prior to the intrusion are 70 particles/200 ml). These data suggest that the bottom may be the source of these particles and are consistent with the idea that organic material was resuspended from the bottom sediments. This may be the case if the particles are broken fecal material. Few F3 have been observed in

samples from the incubation bottles, except for samples collected at the bottom of St. 9, where their numbers hardly change during the incubation.

Conclusions

An intense intrusion of deep water into the main basin of Puget Sound was recorded. The intrusion is saltier (0.8 psu), warmer (0.4° C), and denser (0.6 g/L) than the water residing in the main basin prior to the intrusion (Figure 4). Compared to past studies of intrusions (Cannon and Laird, 1978; Geyer and Cannon, 1982; Cannon et al., 1990) that were mostly observed using mooring data, this intrusion is one of the strongest observed. For average intrusions, changes in salinity are ~0.2 psu (Geyer and Cannon, 1982). While it was suggested (Lavelle et al., 1991) that the summer season should be the season of strongest intrusions, our measurements together with past studies (op. cit.) have shown the spring is a season of very strong intrusions. Reasons for the greater strength of spring intrusions are the maximum diurnal inequality and relative weakness of the neap tides close to the equinox (Holbrook, personal communication) and the weakening of southerly winds that prevail during winter.

Fractionation of pigments data and the data derived using flow cytometry suggest that small cells are better preserved within the intrusion than large cells. The link between the size of particles containing pheopigments and the size of phytoplankton cell and their predators needs further study before it can be used as an indicator of trophic dynamics.

Two classes of small particles, with optical characteristics similar to cyanobacteria, were quantified. The particle with optical properties that resembled coastal cyanobacterial species dominated during our cruises. A third, unidentified group of particles, which does not behave in a similar manner to the phytoplankton, was found in significant concentrations near the bottom of Puget Sound. The most abundant group (F1) was shown to be a useful tracer for downwelling waters. Under dark conditions, it had a half-life time of about six days, a period long enough to be observed through the intrusion penetration and short enough to decrease prior to the entry of a new intrusion.

Winter et al. (1975) have studied the dynamics of pigments during spring and summer in Puget Sound. They found large concentration of pigments (they did not separate chl *a* and pheopigments) to occur at a fortnightly periodicity, in association with increased salinity in the bottom. They have hypothesized that bottom water renewal processes are the underlying mechanism, a hypothesis we were able to confirm. More than 80% of the chl *a* concentration disappeared from the bottom waters within a week time, an indication of the rapid consumption and/or sinking of the pigments in the deep-water intrusion. The impact on oxygen was rapid with a reduction of ~0.6ml/L in one week. Whether the reduction is solely due to the intrusion still needs to be determined.

The predictability of major circulation feature in Puget Sound, as highlighted here for a deep-water intrusion, could be used to maximize the rate of transport of anthropogenic contaminants away from Puget Sound into the Strait of Juan de Fuca. On average, 52% of the water entering Admiralty Inlet from Puget Sound recirculates into other Puget Sound layers (Cokelet et al., 1991). But timing the release of contaminants and adjusting their density, so that the smallest amount gets refluxed into the Sound at the sill, should lower the refluxing ratio of contaminants significantly. Use of numerical models that assimilate hydrographic and wind data at key locations in Puget Sound would increase greatly the ability to accurately predict the circulation in Puget Sound.

Acknowledgment

We would like to thank the Washington Sea Grant Program for supporting this project. Additional funding was provided by the University of Washington Royalty Research Fund. Hal Mojfeld provided tidal data; G. Cannon and J. Holbrook provided information about past intrusions. The data could not have been collected without the help of the technical staff and of the students of the University of Washington School of Oceanography.

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Circulation in Southern Puget Sound's Finger Inlets: Hammersley, Totten, Budd, Eld, and Case Inlets

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Introduction

The seven waterways inland of Devils Head hold the southernmost 2% of Puget Sound's water, and open westward so as to resemble a human hand: the thumb represents Case Inlet, and the four fingers correspond to Hammersley, Totten, Eld, and Budd inlets (Figure 1; McLellan 1954). They are thus known as the finger inlets.

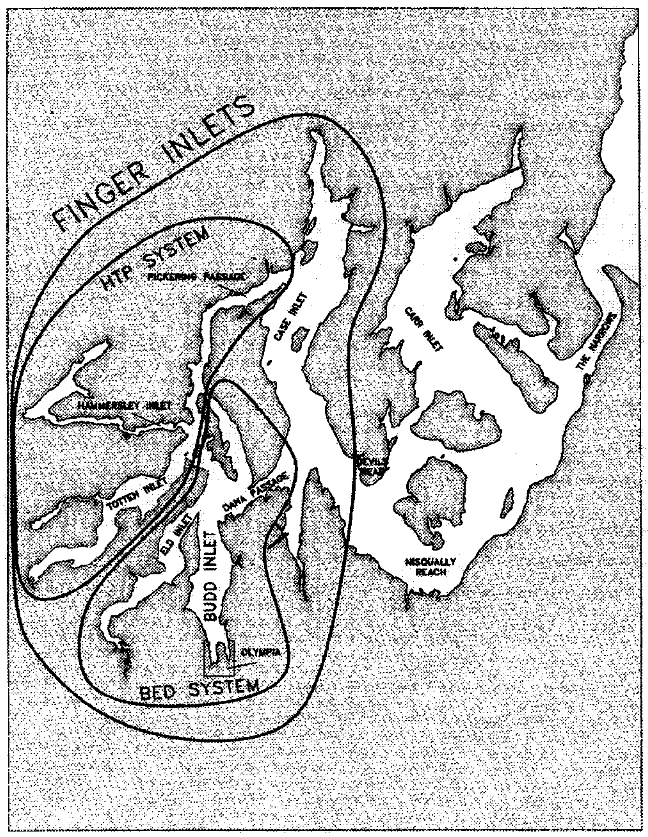

Figure 1. Location of the five finger inlets within Southern Puget Sound. The finger inlets are (named clockwise): Budd Inlet, 2) Eld Inlet, 3) Totten Inlet, 4) Hammersley Inlet, and 5) Case Inlet. The finger inlets are composed of two dynamically distinct groups of water bodies separated by Squaxin Passage: the BED system or group to the east consists of Budd and Eld Inlets and Dana Passage; and the HTP group to the west consists of Hammersley and Totten Inlets and Pickering Passage.

Available oceanographic information has been inadequate, both spatially and temporally, to resolve the relevant oceanographic processes controlling the circulatory exchange amongst the finger inlets. In

addition, as new information has been acquired, important physical processes at progressively smaller scales have been uncovered. To discern the exchange between the finger inlets, five widely differing techniques were explored.

The combined techniques led us to subdivide the finger inlets into two dynamically distinct groups (Figure 1): 1) the eastern, or BED group, designating Budd and Eld inlets, joining Case Inlet through Dana Passage; and 2) the western, or HTP group, designating Hammersley and Totten inlets, joining Case Inlet through Pickering Passage. Additional aspects of the analyses may be found in the Budd Inlet Scientific Study (1998) funded by the Lacey, Olympia, Tumwater, Thurston County (LOTT) partnership of municipalities.

Specifically, the five techniques applied were:

1. To discover the transport pathways, drift cards were released monthly during 1996–1997, and recoveries by the public were tabulated.
2. To confirm the limited exchange between the BED and HTP groups inferred from the drift cards, historical hydrographic data were subjected to a Principal Components Analysis (PCA).
3. To confirm that Squaxin Passage blocks the exchange between the BED and HTP groups, dye was injected into a physical model of the tides within the finger inlets.
4. The blockage was also evident from contrasting the temperature, salinity, and density at both ends of Squaxin Passage.
5. Differences between the water masses discharged by the BED and HTP groups into Case Inlet were inspected by a high-resolution conductivity-temperature-depth transect (CTD; 2-km station spacing).

1. Drift Cards

Drift cards provided the clearest evidence of finger inlet behavior. Before this study, however, few drifting objects (bottles, cards) had been deployed in Southern Puget Sound. To rectify this situation, 9,950 drift cards were deployed. The cards are wooden, measure approximately 3" x 5", and were coated with orange, non-toxic paint to render them readily visible to beachcombers. Each card carried a serial number preceded by 'L' for LOTT, an address, and an 800-telephone number enabling beachcombers to easily report recoveries. The reports were tabulated within 1-mi shoreline segments because most of the cards were found along short stretches of beach in the vicinity of dynamical boundaries.

Fifty cards were released at 15 sites in Budd Inlet, totaling 750 cards during a single day and 8,950 cards summed over the 12 cruises during 1996–1997 (Table 1; Figure 2; encountering a floating dead body prevented 50 cards from being released during Drop 5 at Site 4 on February 11, 1997). The boat drops were made during monthly CTD surveys and were not coordinated with respect to winds or tides.

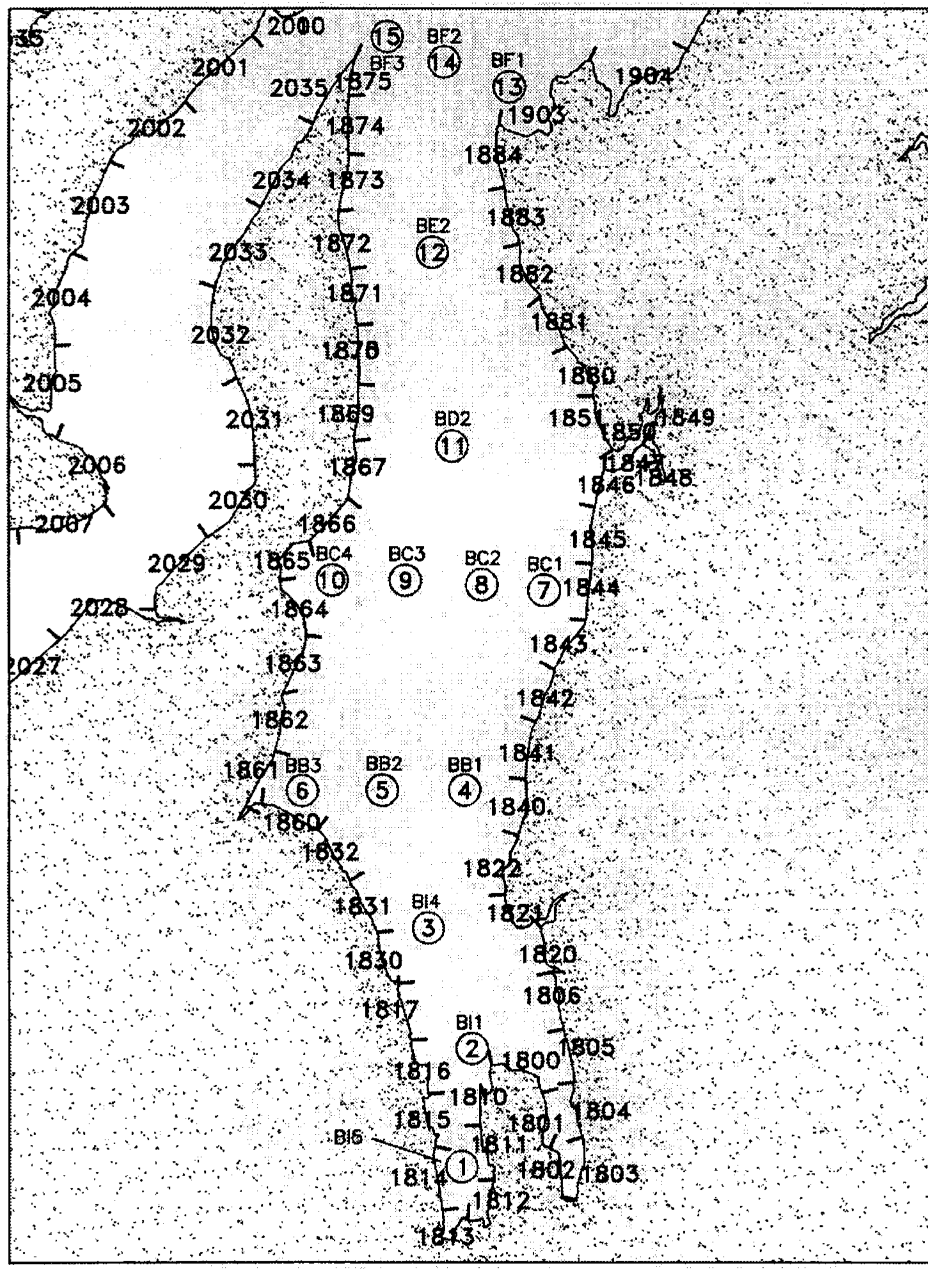

Figure 2. Monthly drift card release sites in Budd Inlet. Circled numbers 1–15 indicate drift card drop sites, numbers between ticks along the shore indicate 0.25-mi long segments in which drift cards were tabulated.

After a few drops, we noticed that very few cards drifted from Budd Inlet to Eld, Totten, and Hammersley Inlets and Pickering Passage. We questioned whether enough beachcombers were there to report cards. Therefore, on January 22, 1997, from a Cessna 172 light aircraft flying at 500-ft altitude, 16 batches of 50 cards were dropped within half an hour along the central axes of the Budd, Eld, Totten, and Hammersley Inlets, and another four batches along Pickering Passage (Figure 3). To maximize the time the cards drifted within the five water bodies, thereby providing beachcombers optimal recovery opportunities, the cards were air-dropped on a flood tide.

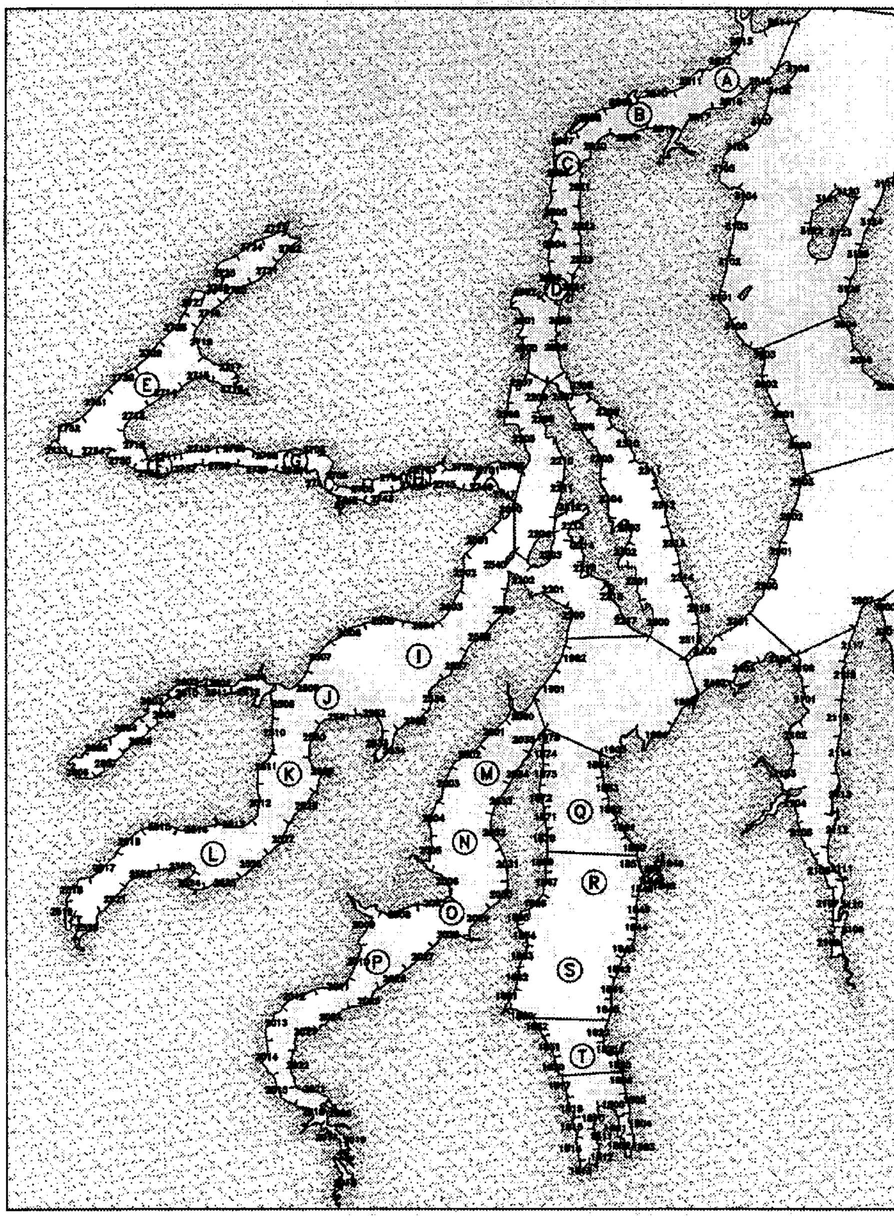

Figure 3. Air-drop drift card release sites. Twenty sites where drift cards were released on January 22, 1997 from a small aircraft: sites A–D in Pickering Passage; sites E–H in Hammersley Inlet; Sites I–L in Totten Inlet; sites M–P in Eld Inlet; and sites Q–T in Budd Inlet. Numbers between ticks along the shore indicate segments in which drift cards were tabulated.

All totaled, beachcombers reported 51% of the Budd Inlet drops as of January 14, 1998, when the tabulations were terminated to meet reporting deadlines. The percentages recovered from the air-drops were comparable for each inlet (sites are shown in Figure 3): 51.5%, Pickering Passage (Sites A–D); 42.5%, Hammersley Inlet (Sites E–H); 55.0%, Totten Inlet (Sites I–L); 35.5%, Eld Inlet (Sites M–P); and 49.5%, Budd Inlet (Sites Q–T). Therefore, adequate numbers of walkers combed the beaches around each of the finger inlets.

Table 1. Drift Card Releases in Budd Inleta

Drop number	Date	Number of cards released
1	October 2, 1996	750
2	November 6, 1996	750
3	December 5, 1996	750
4	January 8, 1997	750
5	February 11, 1997	750
6	March 19, 1997	750
7	April 16, 1997	750
8	May 7, 1997	750
9	June 11, 1997	750
10	July 21, 1997	750
11	August 20, 1997	750
12	September 30, 1997	750
12 cruises		8,950 cards released

* Drop-site locations are displayed in Figure 2.

Of the 8,950 cards released in Budd Inlet, only 7.3% of the recoveries occurred west of Squaxin Passage, 6.0% of which came from upper Case Inlet (Figure 4). Three out of four recoveries (75.9%) were found either in Budd Inlet (31.0%) or exited through Dana Passage (44.9%). Of the 400 cards air-dropped in Hammersley and Totten Inlets, the bulk (43.6%) were found in the inlets themselves, and 20.0% exited through Dana Passage with 8.7% found in upper Case Inlet (Figure 5). These results suggest that Squaxin Passage blocks cards drifting westward from Budd Inlet, but allows a substantially greater fraction to pass eastward through Dana Passage (Figures 4 and 5).

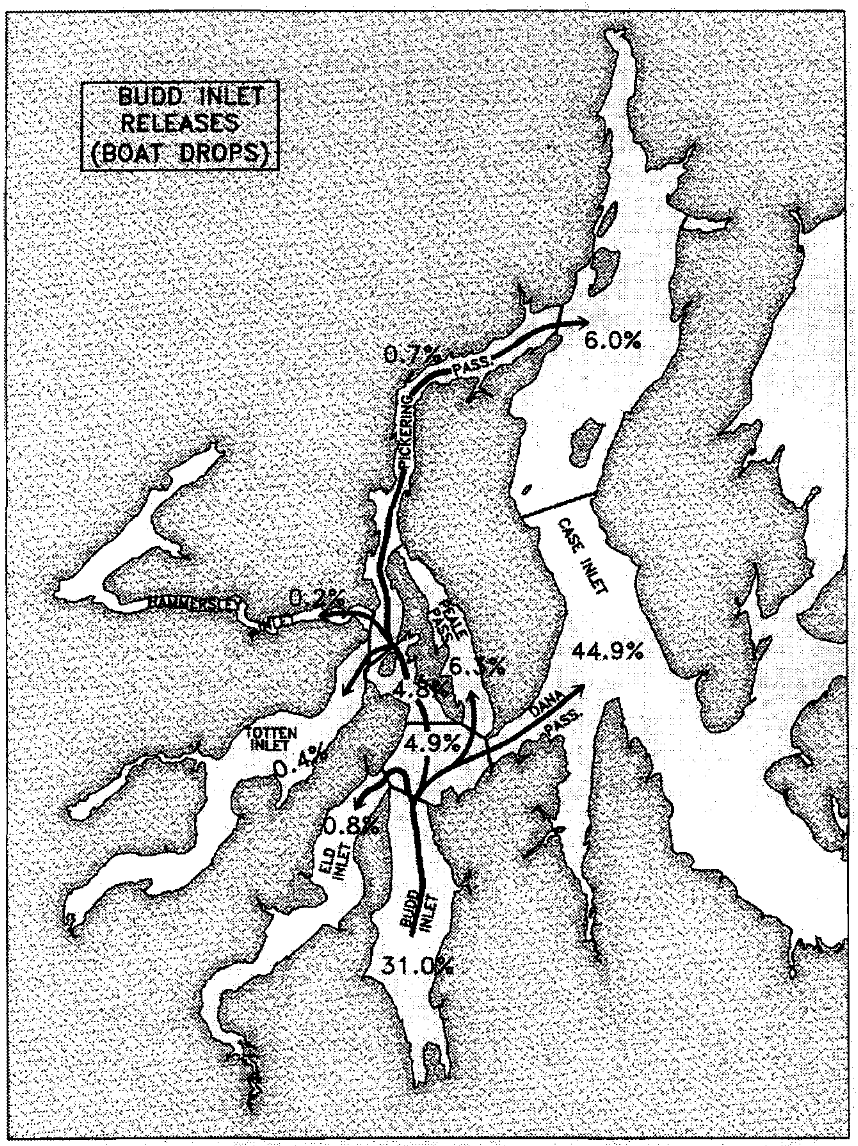

Figure 4. Drift card pathways from Budd Inlet. Shown are percentages of the total number of cards recovered (4,609) from 8,950 total cards released in Budd Inlet from October 1996 through September 1997 (see Table 1 and Fig. 1 for release dates and locations). Lines represent divisions between water bodies. Most cards were either found in Budd Inlet (31.0%) or exited through Dana Passage into Case Inlet (44.9%), whereas a smaller percentage traveled via Squaxin (4.8%) and Pickering (0.7%) passages to reach upper Case Inlet (6.0%). Very few cards were found in Eld (0.8%), Totten (0.4%), and Hammersley (0.2%) Inlets.

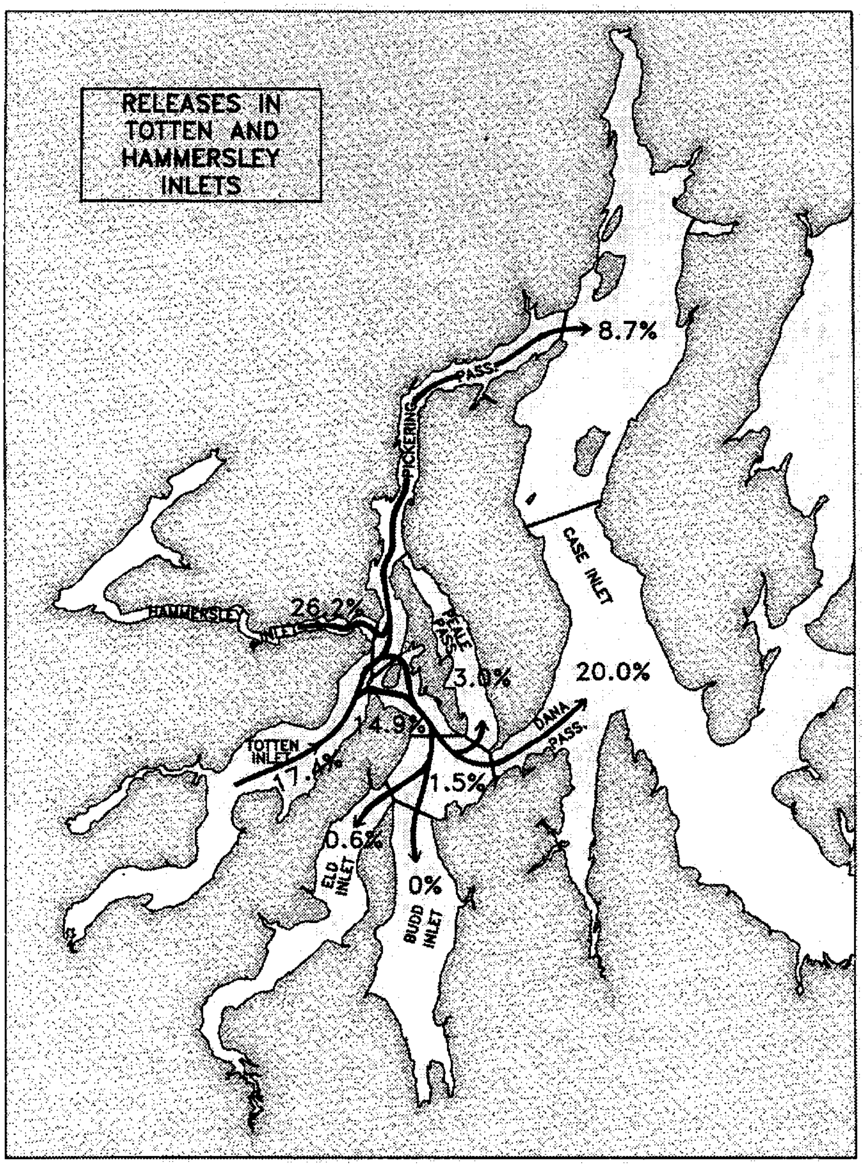

Figure 5. Drift card pathways from Totten and Hammersley Inlets. Shown are percentages of the total number of cards recovered (195) from 400 total cards air-dropped in Totten and Hammersley Inlets on 22 January 1997 (see Fig. 3 for locations). Lines represent divisions between water bodies. Most cards were either found in Totten and Hammersley Inlets (43.5%) or exited through Pickering Passage into upper Case Inlet (8.7%), whereas a smaller percentage travelled via Squaxin (14.9%) and Dana passages to reach lower Case Inlet (20.0%). Very few cards were found in Eld (0.6%) or Budd (none) Inlets.

Tabulations in the shoreline segments pinpointed the blockage within Squaxin Passage (Figure 6). Of the 234 cards recovered in Squaxin Passage and approaches, 11% were found to the west and 89% to the east of Hope Island. Of the latter category, most came from three embayments along the western shores of Squaxin Island.

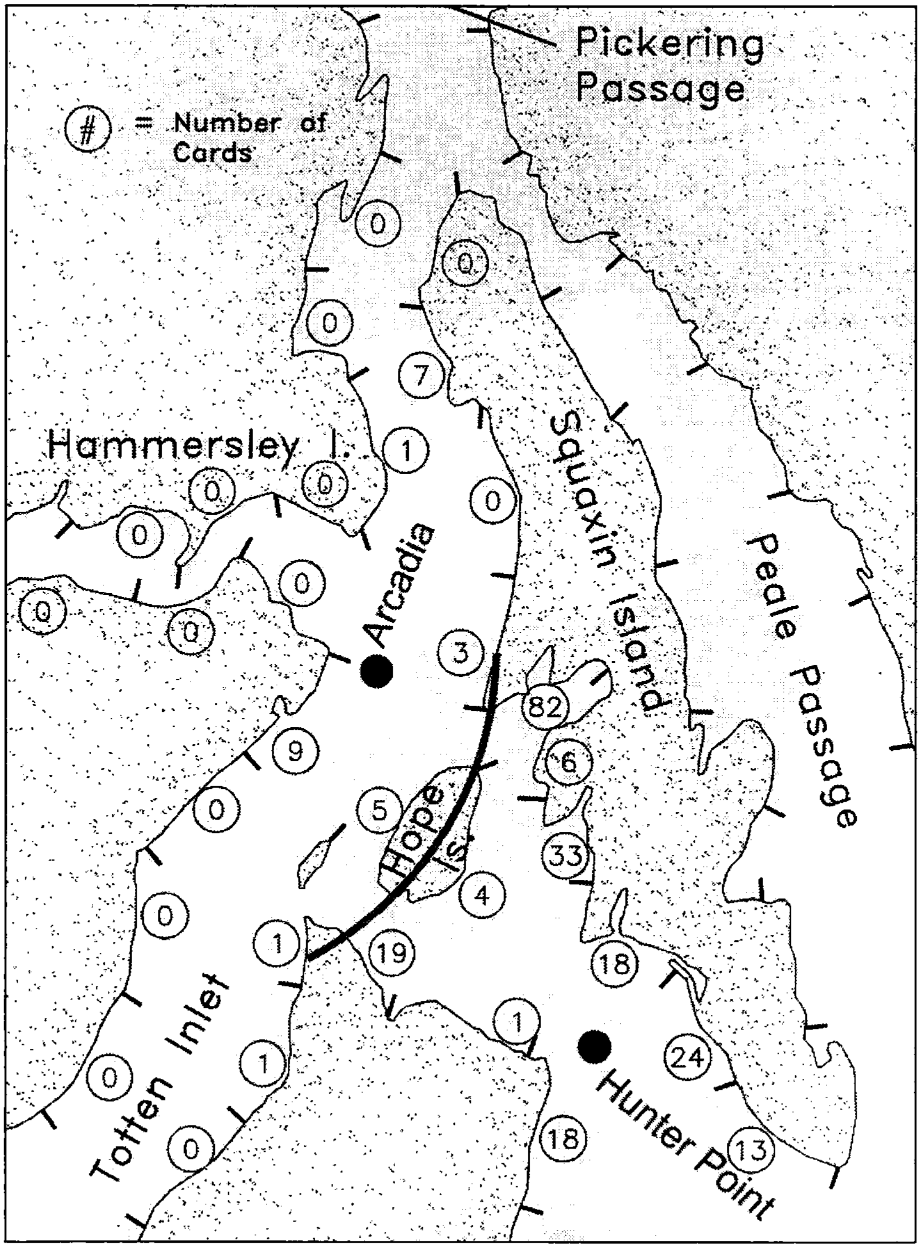

Figure 6. Drift card recoveries in Squaxin Passage. Of the 234 cards released in Budd Inlet and recovered in the shoreline segments in Squaxin Passage, as shown here, 90% were found east of Hope Island and 10% to the west. The thick solid line represents the dynamical blockage between the BED and HTP groups of finger inlets, and the two dots show the locations where water properties were contrasted between the east (Hunter Point) and west (Arcadia) ends of Squaxin Passage.

To examine how the cards exited the BED and HTP groups into Case Inlet, drift card recoveries were tabulated as histograms within 40 slices from the head of Case Inlet through Nisqually Reach (Figures 7 and 8). Differences between the groups became evident by contrasting the histograms from four drift card releases (Figure 8a–8d): a) 8,950 cards boat-dropped in Budd Inlet, b) 400 cards air-dropped in Eld and Budd inlets, c) 200 cards air-dropped in Pickering Passage, and d) 400 cards air-dropped in Totten and Hammersley inlets.

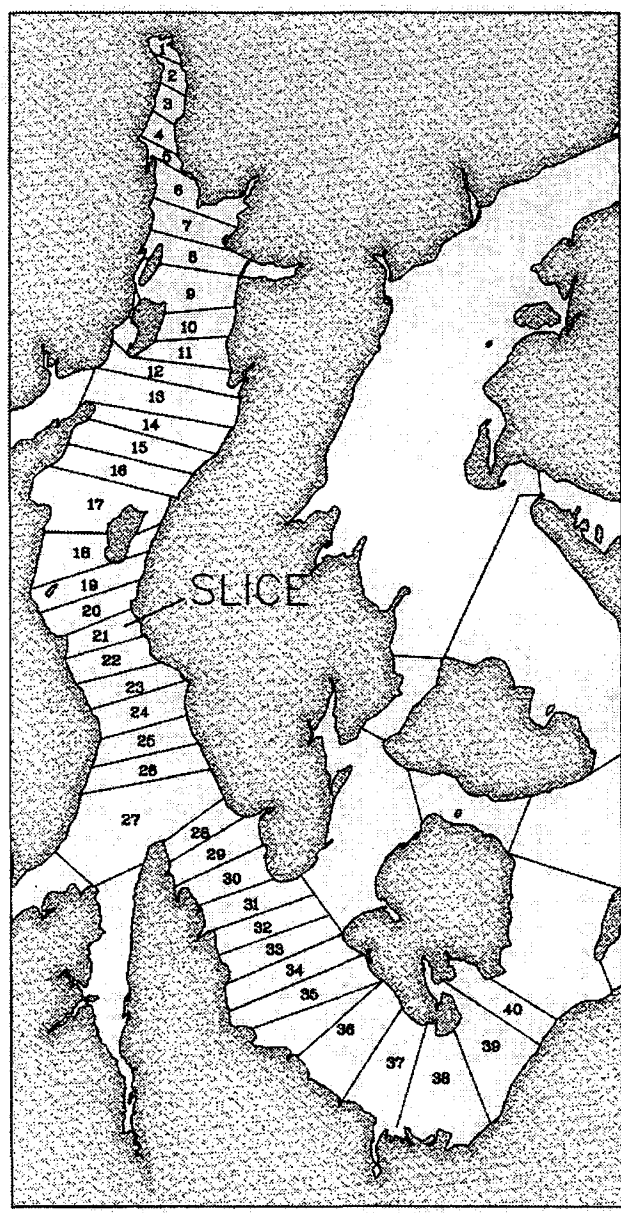

Figure 7. Forty slices along Case Inlet between Nisqually reach and the head of Case

These histograms showed that the cards accumulated in two modes along Case Inlet in the vicinity of the discharges from Dana and Pickering passages. Because of the modal separation along Case Inlet, the drift card recovery maps shown in Figures 4 and 5 were constructed assuming no exchange between the slices of upper Case Inlet (slices 1–19) and lower Case Inlet (slices 20–40).

2. Principal Component Analysis

Principal component analysis (PCA) is a statistical procedure that combines various parameters into groups that explain maximal amounts of environmental variability. To conduct the PCA, precipitation and river runoff were compared with historical salinity measurements. In the late 1950s, to address concerns that pulp mill effluents were affecting oyster harvests, the finger inlets were surveyed by the University of Washington (UW) (Olcay, 1959), ITT-Rayonier Corporation (ITT, unpubl. data), and the Washington State Department of Fisheries (unpubl. data).

Fifteen cruises were selected for the PCA by culling the best quality, most extensive data available during 1957–1958 (see Olcay, 1959). The ITT data were used to estimate values missing in the UW data for Hammersley Inlet during spring and summer 1957. River discharge into Budd Inlet was estimated using historical data from the U.S. Geological Survey (USGS) gauge on the Deschutes River at Mt. Rainier near McKenna. Runoff for the HTP group was represented by the USGS gauge on Goldsborough Creek. Rainfall onto Budd Inlet was derived from data at Olympia Airport, and for the the HTP group from the Cooperative Weather Station in Shelton.

The first principal component explained 56% of the total variance and represents the signals' annual variation. The second component, accounting for 27%, is the response of the inlets to freshwater inputs. The third component, equalling 5%, represents the difference in inlets' response to rainfall versus runoff.

The PCA component scores showed that the BED and HTP group responses are distinctly different (Figure 9). The variations in salinity at Shelton (SH and sh, Figure 9) are most similar to those at Arcadia and in Totten Inlet (AR, ar, TN, tn). These HTP inlets respond to rainfall in preference to the river runoff. Note also that the salinity variations in the BED inlets tend to be inversely coupled to freshwater inputs. That is, salinity values increase in response to increased fresh water in the lower layers of Case Inlet, Budd Inlet, and Dana Passage, and in the northern portion of Pickering Passage.

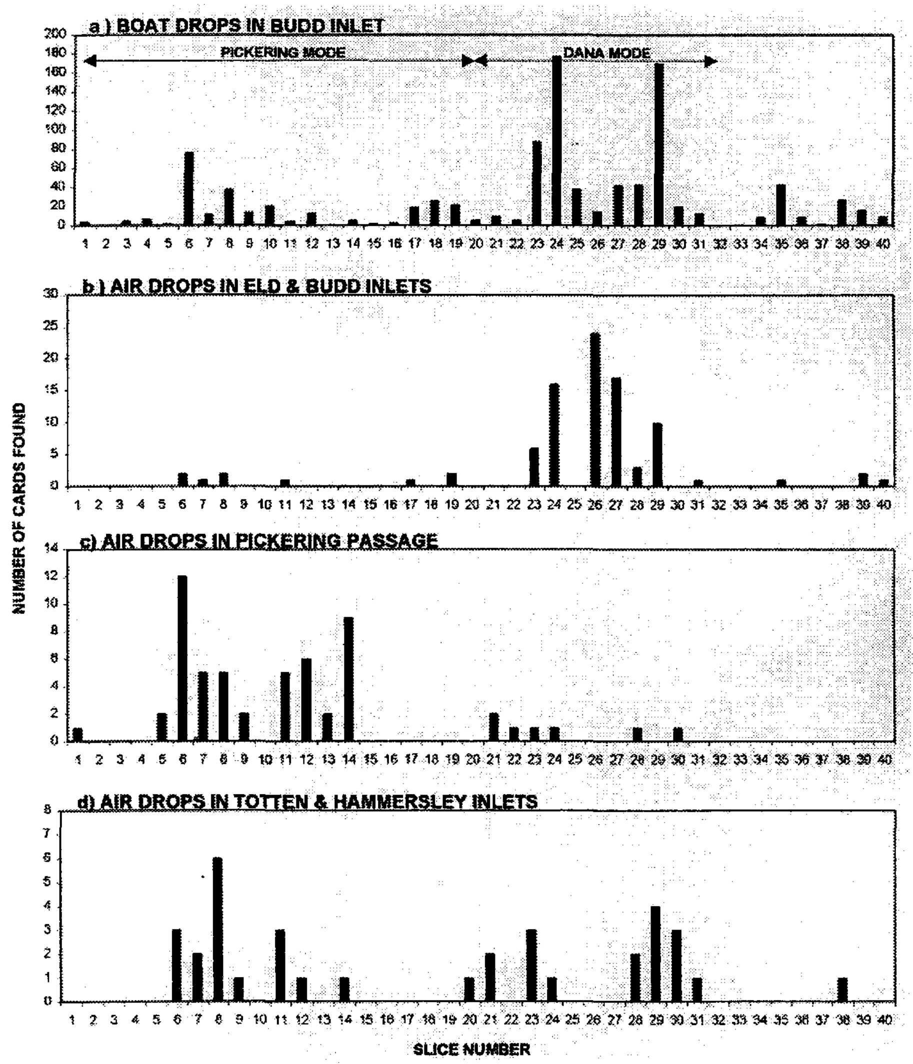

Figure 8. Histograms of drift card recoveries along Case Inlet and Nisqually Reach. a) drift cards found from the 8,950 cards released in Budd Inlet; b) number of cards found from the 400 cards air dropped into Eld and Budd inlets (BED system); c) number of cards found from the 200 air-dropped into Pickering Passage (HTP system); and d) number of cards found from the 400 air-dropped into Totten and Hammersley inlets. The slice numbers begin at the head of Case Inlet and end off Nisqually Reach (Figure 7). Histogram groupings between slice numbers 1–19 correspond to cards from Pickering Passage, and between slice numbers 20–31 from Dana Passage.

The fact that the HTP group displays a different response is not proof that it is decoupled from the BED system. At the very least, the PCA suggests that the two groups are dynamically distinct. Further, the transport between them through Squaxin Passage is not so large as to mask these distinctions.

3. Physical Model

A hydraulic model was constructed at Shoreline Community College to simulate the tides in the finger inlets. Horizontal and vertical scales equalled approximately 196:1 and 11.4:1, respectively. There were no inputs of fresh water. Water flux through Squaxin Passage was examined by staining Totten Inlet with green and Budd Inlet with red dye. Sequences of photos through tidal days showed the relative behavior of the BED and HTP groups.

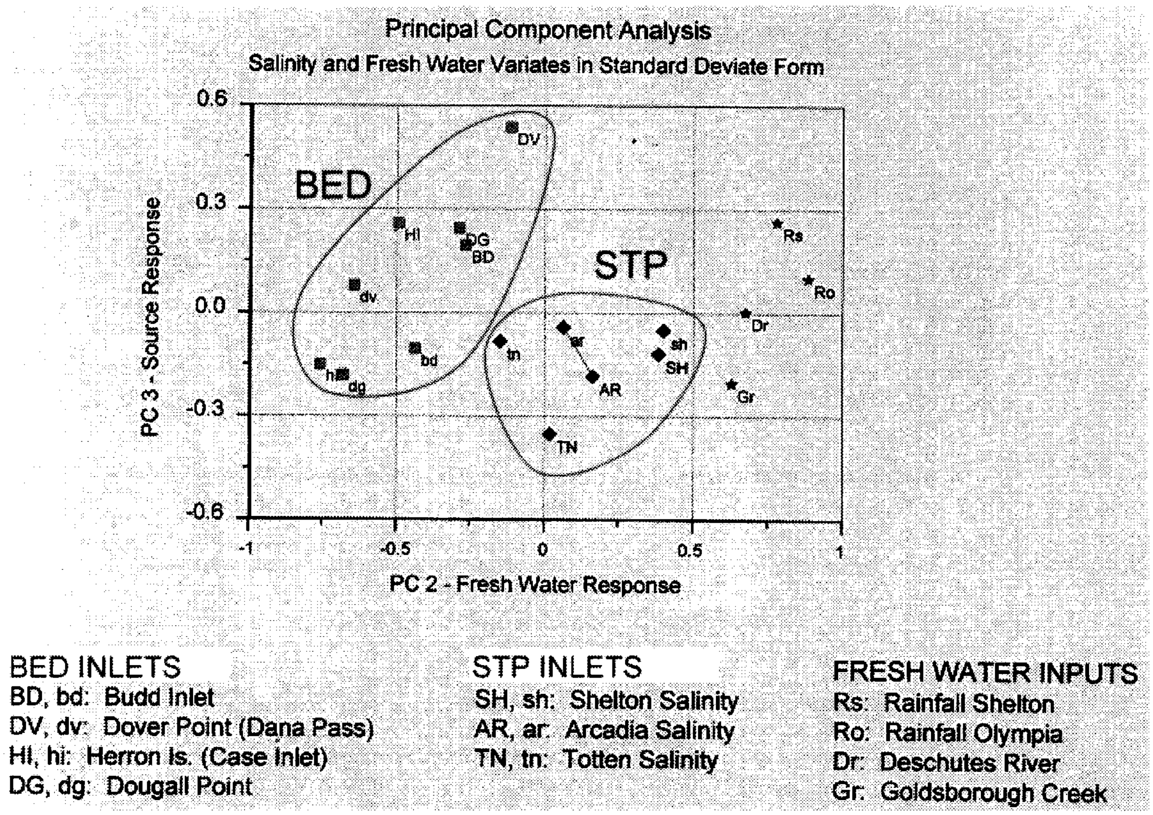

Figure 9. Principal component analysis. Clusters of points corresponding to the BED or eastern groups of inlets, and the HTP or western inlets, have been circled.

After several tidal cycles, the green dye worked its way northward through Pickering Passage entering upper Case Inlet. Small amounts of green dye flowed southward into Peale Passage, with a minor fraction moving toward Budd Inlet. The red dye traveled towards and through Dana Passage, filling lower Case Inlet. Some red dye entered Peale Passage. Repeated simulations revealed no red dye entering the Totten, Hammersley, Pickering system, though dye from that system occasionally was transported toward Budd and exited Dana Passage.

4. Blockage in Squaxin Passage

If Squaxin Passage does block the flow between the BED and HTP groups, the water properties at the Passage's extremities should differ. To explore this hypothesis, temperature, salinity and density at 0 and 10 m depths at west (Arcadia Station) and east (Hunter Point Station) ends of Squaxin Passage were compared (Figure 6). It can be seen in Figures 10 and 11 that, through the water column, water is always more dense at the east than at the western end of Squaxin Passage. The density difference averages one sigma-t unit, a substantial value in the context of other Puget Sound water bodies. The density difference occurs because the waters west of Squaxin Passage are almost always warmer and fresher than those to the east.

In the absence of a dynamical mechanism, higher density water normally flows into regions of lower density. Though the dynamical nature of the Squaxin blockage remains unknown, there can be little doubt that it does separate the BED and HTP groups.

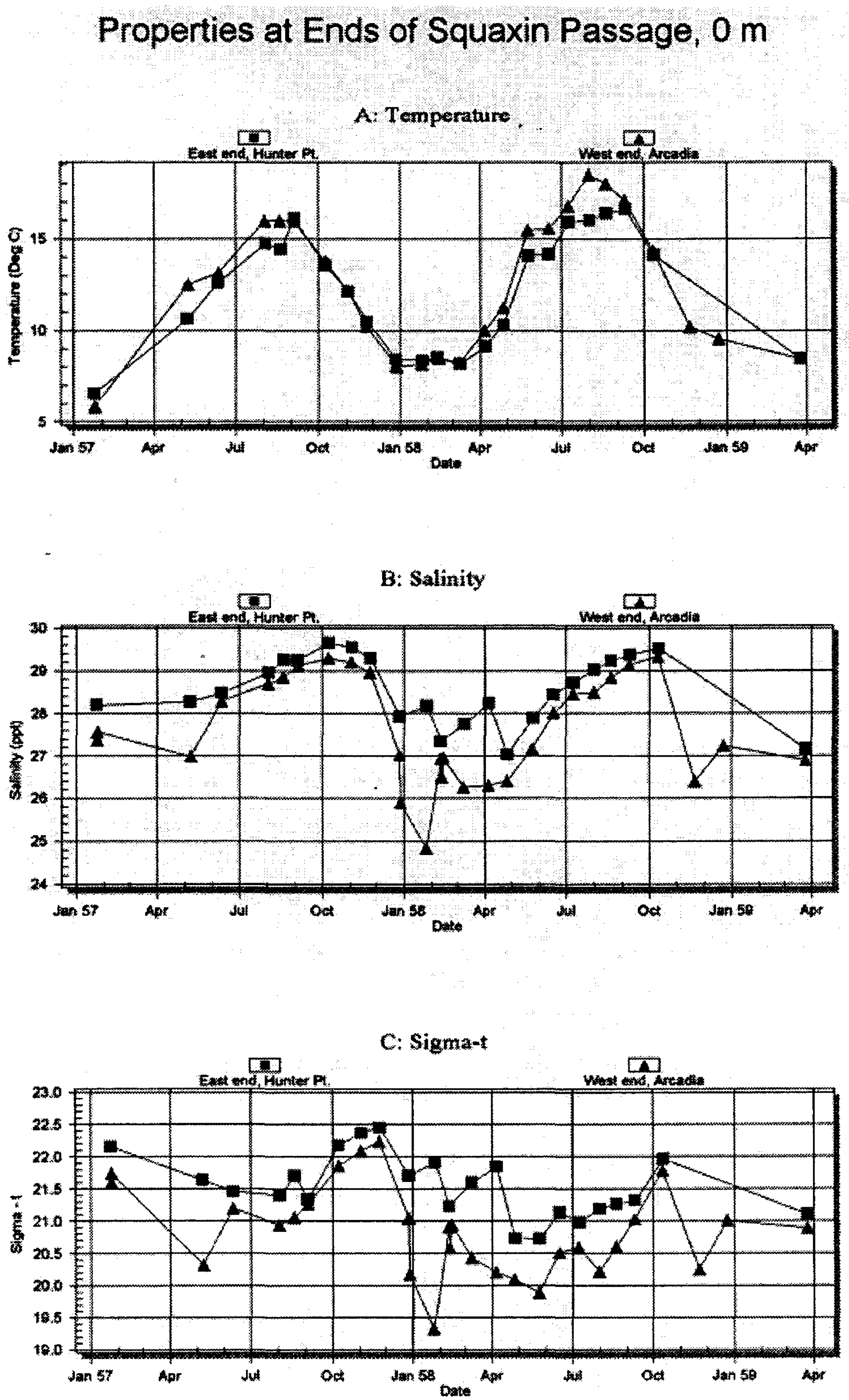

Figure 10. Water contrast across Squaxin Passage at the sea surface. The differences across Squaxin Passage were represented by temperature (a), salinity (b) and density (c; sigma-t units) observed at Hunter Point representing BED System and Arcadia representing the HTP System. Note that the HTP waters are almost always fresher, warmer and less dense than those in the BED group.

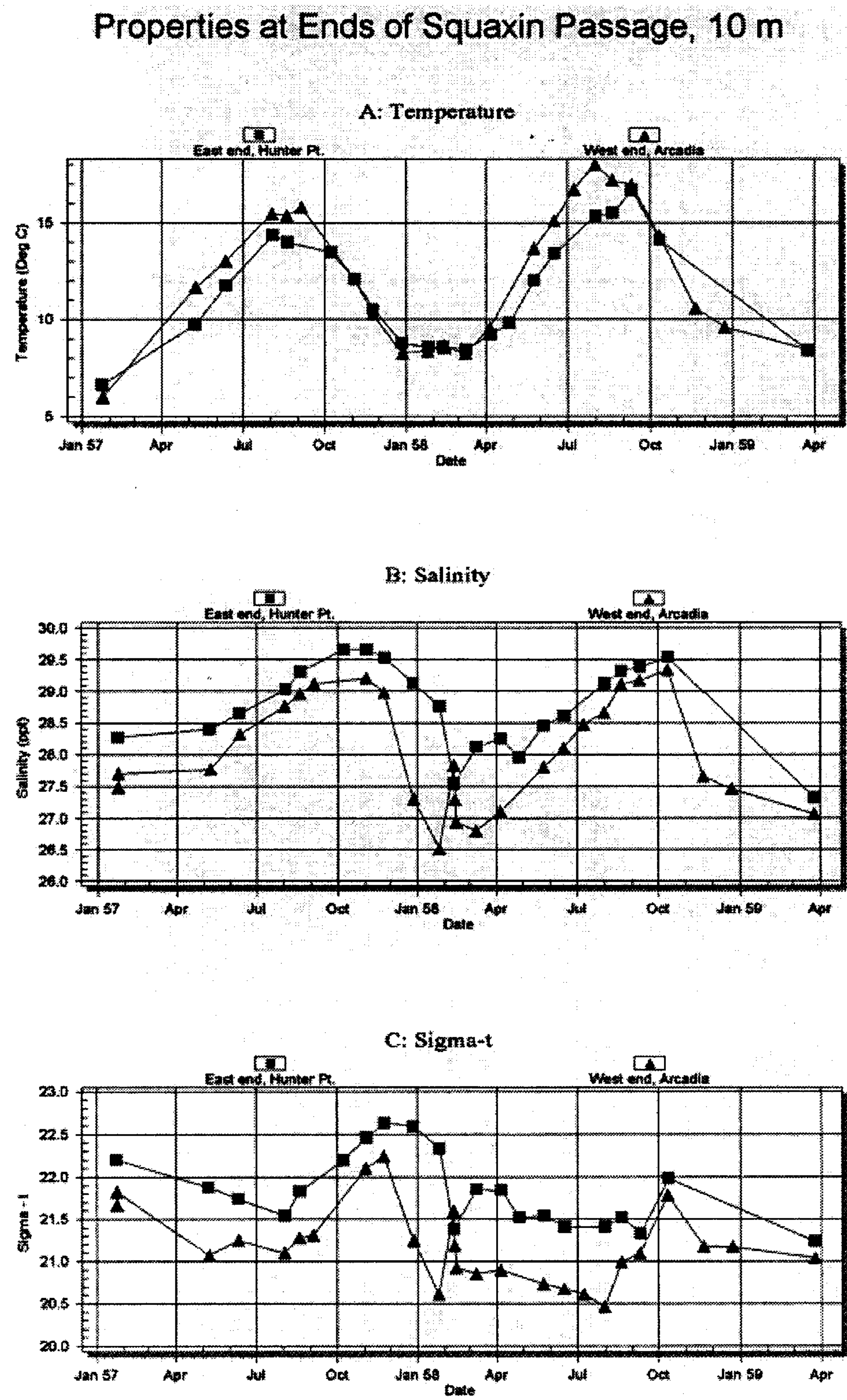

Figure 11. Water contrast across Squaxin Passage at 10-m depth. The difference across Squaxin Passage were represented by temperature (a), salinity (b) and density (c; sigma-t units) observed at Hunter Point representing BED System and Arcadia representing the HTP System. Note that the HTP waters are almost always fresher, warmer and less dense than those in the BED group.

5. Case Inlet High-Resolution CTD Transect

The BED and HTP groups discharge via Dana and Pickering Passages into lower and upper Case Inlet, respectively. Based on the foregoing analyses, we hypothesized that the differences between BED and HTP effluents would be reflected in Case Inlet's water mass structure. Prior to this time, however, Case Inlet water properties had been sampled at widely spaced intervals (~ 5 km; Collias et al., 1974). To obtain a resolution comparable to that of the drift card histograms, 19 CTD profiles were taken at 2-km intervals from the Nisqually River to the head of Case Inlet (Figures 12–17).

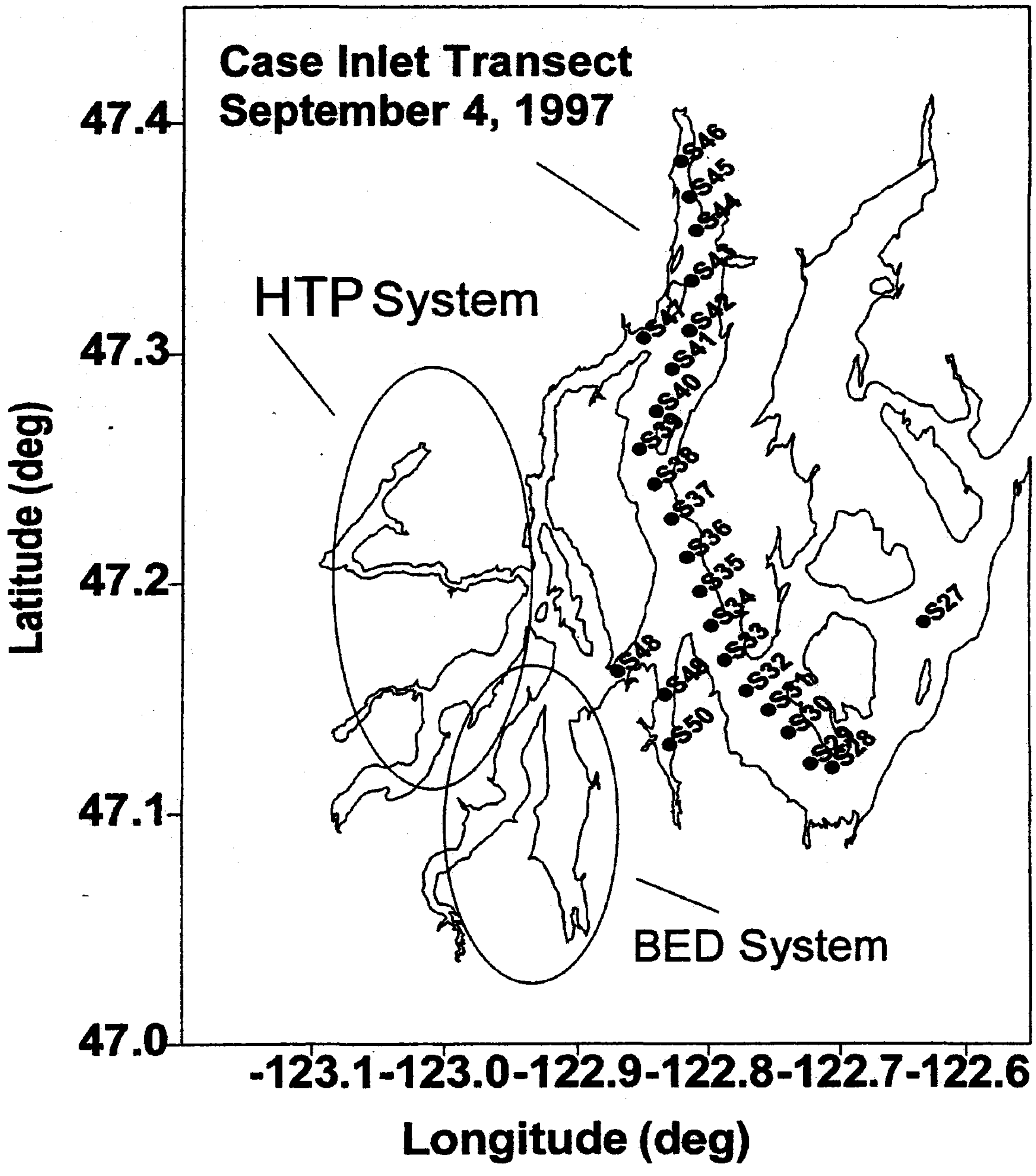

Figure 12. Case Inlet high-resolution transect. On September 4, 1997 CTD profiles were obtained from the Research Vessel Barnes at 19 stations spaced about 1 mi apart, from off the mouth of the Nisqually River on the south to the head of Case Inlet on the north.

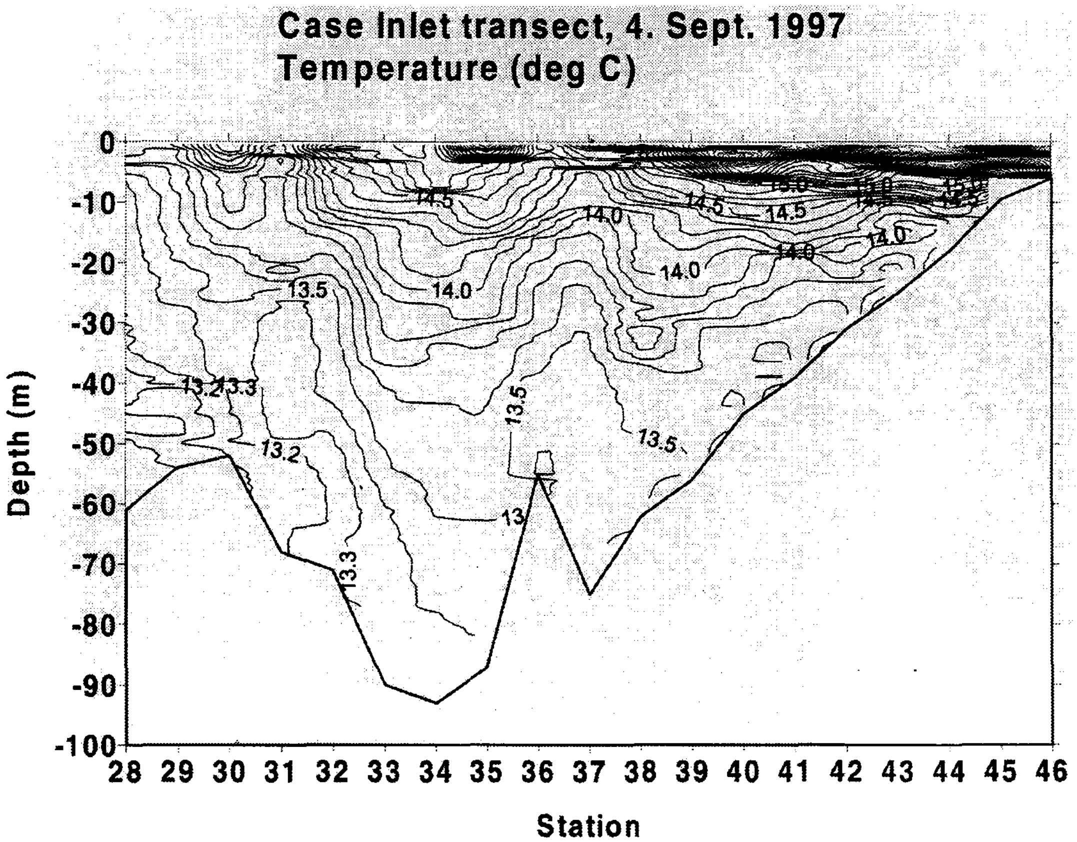

Figure 13. Case Inlet high-resolution transect: temperature contours.

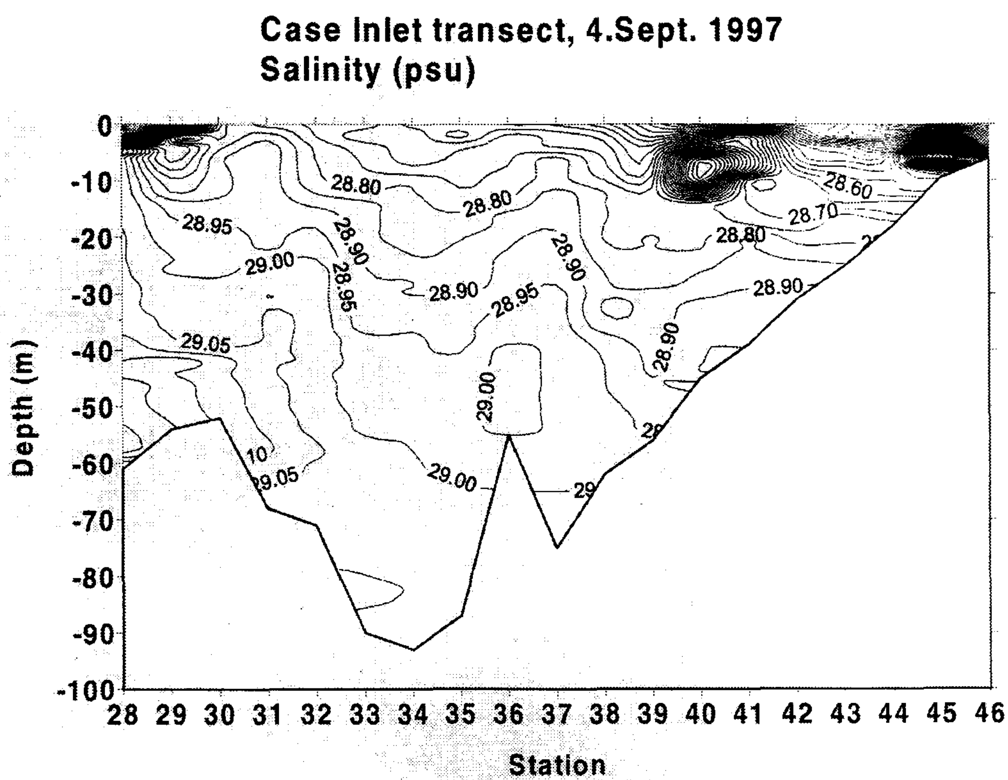

Figure 14. Case Inlet high-resolution transect: salinity contours.

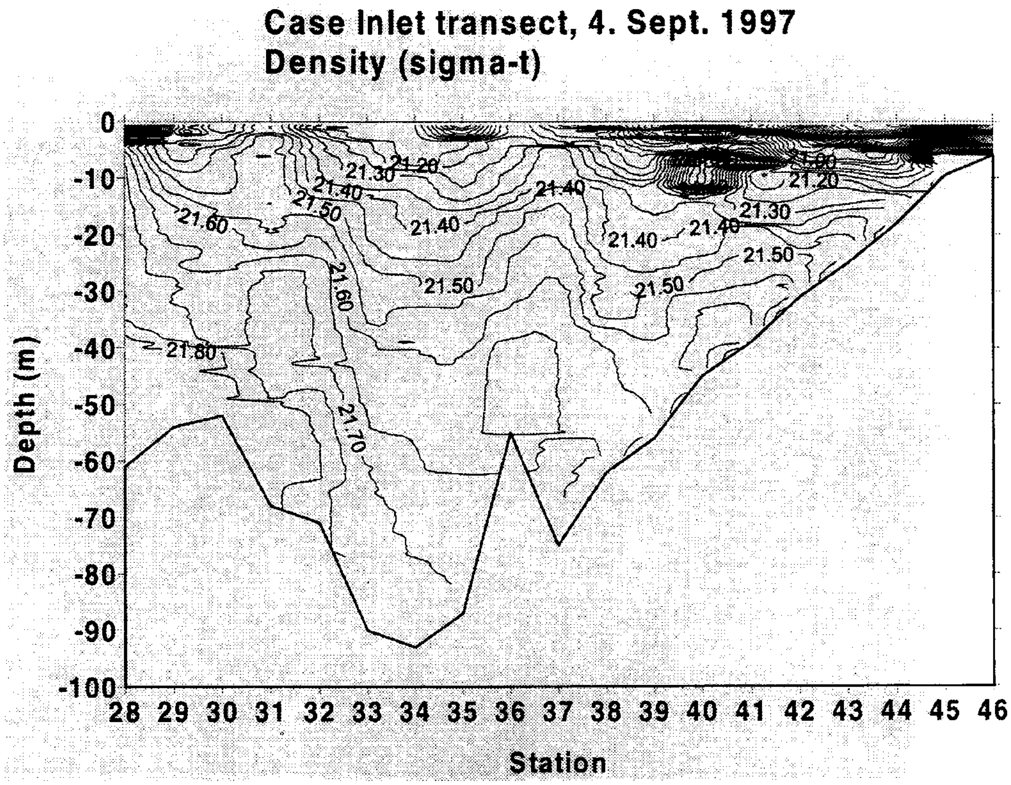

Figure 15. Case Inlet high-resolution transect: density contours (sigma-t units).

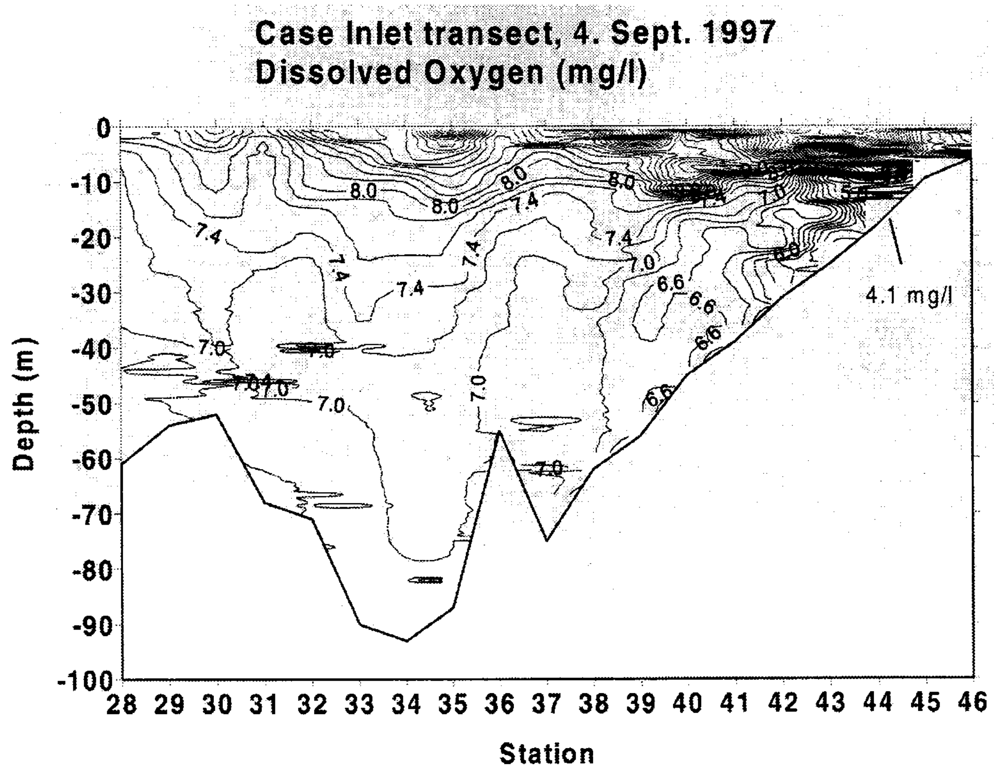

Figure 16. Case Inlet high-resolution transect: dissolved oxygen contours.

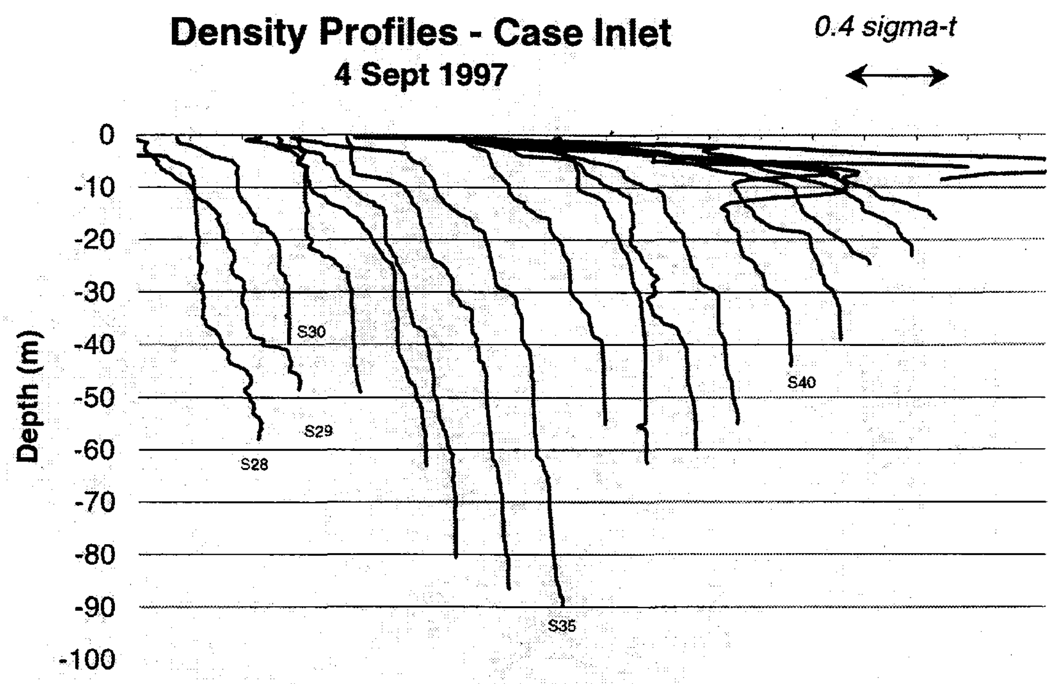

Figure 17. Case Inlet high-resolution transect: density profiles.

Contours of temperature and salinity (Figures 13, 14) showed relatively warm, saline water parcels, measuring ~2 km in horizontal extent, exiting from Pickering Passage. Because their density equaled that of the deepest water, these parcels probably sank to Case Inlet's greatest depths. Toward the end of summer, warm air temperatures apparently evaporate more fresh water than precipitation and runoff supply. This produces high salinities, especially in the Totten and Little Skookum inlets.

Density profiles in Case Inlet indicate regions of homogeneous water separated from one another by sharp gradients, a lenticular structure reminiscent of Puget Sound's Main Basin where discrete water parcels are produced by intense vertical mixing in The Narrows (Figures 15 and17). The parcels in Case Inlet are likely produced by strong tidal mixing in Dana Passage.

To delineate between the origin of different water masses, data from all depths were plotted on a temperature-salinity (T-S) diagram (Figure 18). The deep-water end point at the Nisqually station (28), while having the coldest value on the T-S diagram, has a density nearly equal to those at stations 40 and 45 (nearly 22 sigma-t units). Surprisingly, the maximum densities at stations 40 and 45 are at intermediate depths and, because they are denser than surrounding water, identify sinking water masses. Since the temperature at stations 40 and 45 monotonically decreases with depth, the high density is due to a subsurface salinity maximum. Therefore, at the time of this cruise it was apparent that these anomalously dense water masses were being formed by evaporation in the HTP group. Station 40, south of Pickering Passage in Case Inlet, was sampled on an ebbing tide, whereas station 45, north of the passage, was sampled on a flood. We presume that tidal advection accounts for these multiple encounters of saline Pickering water.

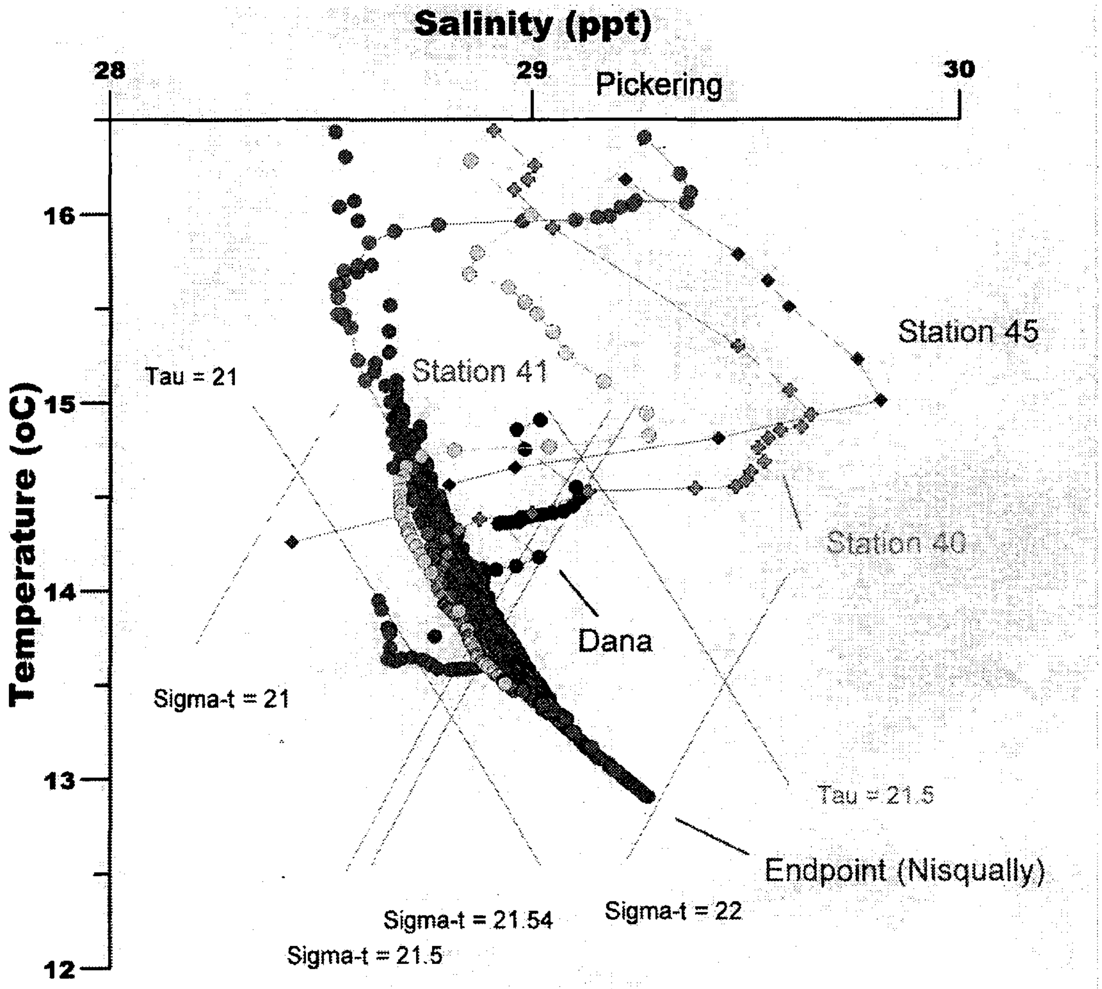

Figure 18. Temperature-salinity diagram for high-resolution survey.

The bulk of the temperature and salinity points lay parallel to lines of constant spiciness (tau), which indicates that these points are insulated against sources and sinks of spiciness (heat and salt). The individual CTD casts (stations 40, 41, 45, and 48) joined by continuous lines on the T-S diagram, that repeatedly cross lines of constant density occur at locations where water masses are either rising or sinking.

The high-resolution survey showed Case Inlet's water mass structure as follows (Figure 19): a) plume of diluted Nisqually River water; b) dense water intruding over the sill (c) off the Nisqually River delta; d) net outflowing layer above the depth of no-net-motion (e) at approximately 20 m; f) net inflow of deep water into Case Inlet; g) parcel of dense water detached from the main mass of intruding water (b); h) Dana Passage cross-section; i) water parcel upwelled along vertical arrow into the surface waters of Dana Passage; j) parcels of water formed in the HTP system and ejected from Pickering Passage poised to sink to the bottom of Case Inlet; k) parcel of water formed in the BED system; l) densest water at bottom of Case Inlet; and m) a zone of depressed dissolved oxygen concentration (Figure 16).

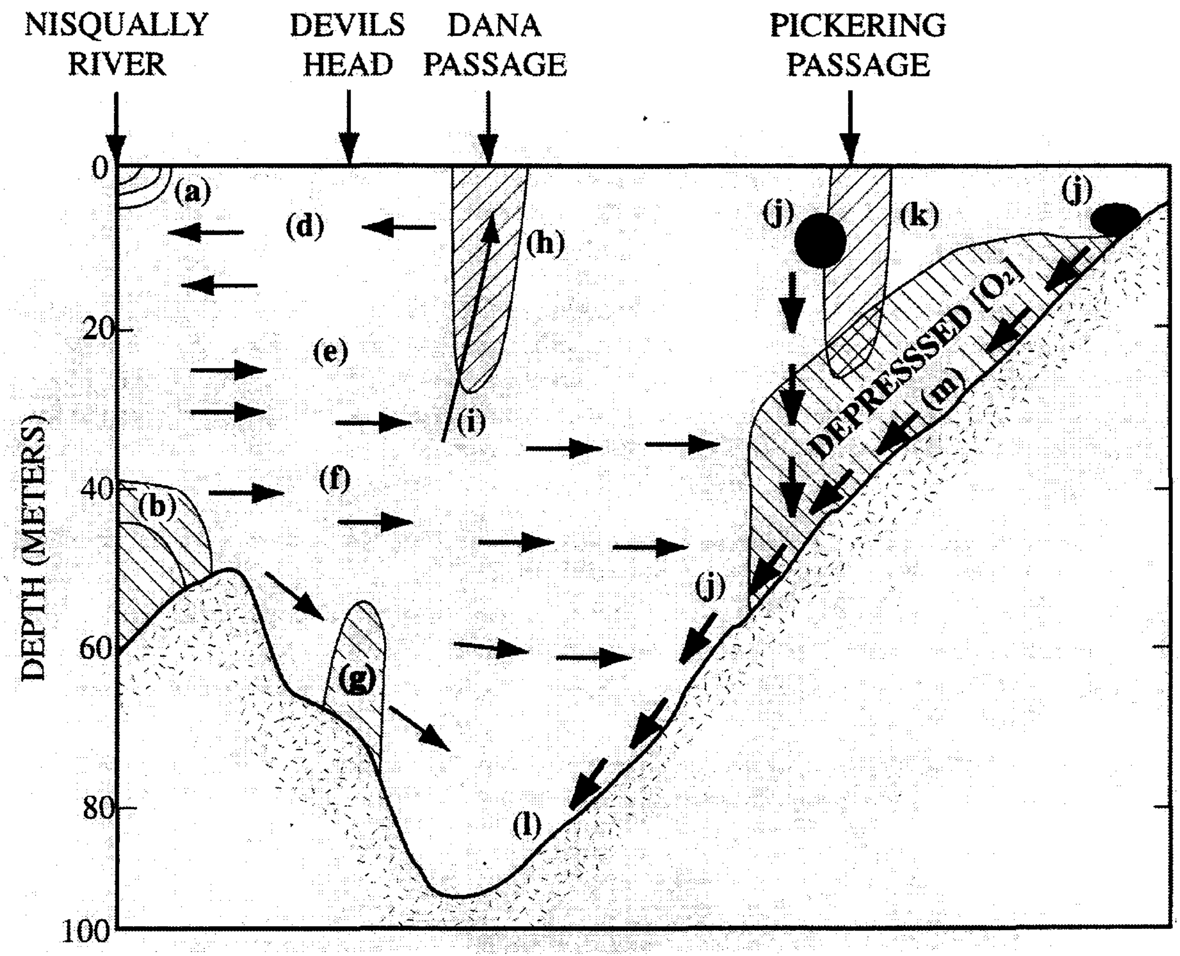

Figure 19. Case Inlet schematic water structure from the Nisqually River (left) to the head of Case Inlet (right). Based on observations of temperature, salinity, density and dissolved oxygen made on September 4, 1997, the schematic was derived with the following elements: (a) plume of diluted Nisqually River water; (b) dense water intruding over the sill (c) off the Nisqually River delta [below (a)]; (d) net outflowing layer above the depth of not-net-motion (e) at approximately 20 m depth; (f) net inflow of deep water into Case Inlet; (g) parcel of dense water detached from the main mass of intruding water (b); (h) Dana Passage cross section; (i) water parcel upwelled along vertical arrow into the surface waters of Dana Passage; (j) parcels of dense water formed in the HTP group and ejected from Pickering Passage (k) poised to sink to the bottom of Case Inlet at l, densest water at bottom of Case Inlet equals 21.7 sigma-t units; (m), zone of depressed dissolved oxygen.

Conclusions

The five analytical approaches (drift cards, PCA, physical model, historical water properties, high-resolution survey) support one another in revealing a unique collective behavior to the water circulation in the finger inlets west of Devils Head. From them, Southern Puget Sound's finger inlets may be grouped into the BED and HTP groups which discharge differing water masses into Case Inlet, including: 1) lenses of salty HTP water spilling from Pickering Passage into Case Inlet; 2 and 3) shallow surface plumes extending from the head of Case Inlet and from the Nisqually River; 4) well-mixed BED effluent from Dana Passage separating the freshwater plumes; and 5) denser Southern Puget Sound water intruding over the Nisqually Reach sill.

The tides are instrumental in flushing the finger inlets, but the details differ between the western and eastern inlets. For Budd and Eld inlets, the deep waters lying off the mouth of Dana Passage are

closely linked by the mixing in Dana Passage, and periods of high river runoff may lead to enhanced transport in the Devils Head and Gordon Point reaches, which paradoxically appears to enhance the flow of deep salty water into the region. The HTP group does is not closely coupled to this deep water in the same fashion as at the BED group, which flushes primarily through Pickering Passage, the primary modulation to their tidal transport being associated with rainfall.

Determining why Squaxin Passage blocks the exchange between the BED and HTP groups will require detailed, local hydrographic, current meter, and hydrodynamical modelling studies.

Acknowledgements

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Dispersion of 1,000 Drift Cards Released Over Victoria's Sewage Outfalls

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Introduction

Drift cards, thin buoyant cards imprinted with messages, are useful for measuring the near-surface currents of marine water bodies (Ebbesmeyer and Coomes, 1993). The cards, or in some cases bottles, are released and drift with winds and currents until they beach. Data from recoveries help identify natural collection zones for debris, and help characterize the flushing of inlets or embayments (Ebbesmeyer et al., 1991; Ebbesmeyer et al., 1998a). These data also aid in verifying results from hydrodynamic models (Ebbesmeyer et al., 1991). Results from studies of both active and passive methods of drifter recovery show that drift cards primarily measure near-surface currents, not the variability of human activity along the shore (Ebbesmeyer et al., 1991).

In Puget Sound, Juan de Fuca Strait, and Georgia Strait, scientists have released on the order of 50,000 drifters over the last half-century (Ebbesmeyer and Coomes, 1993; Ebbesmeyer et al., 1995; Ebbesmeyer et al., 1998a; Ebbesmeyer et al., 1998b). Prior to this study, however, only a few satellite-tracked drifters have been released in Victoria Bight (hereafter, the Bight).

Because the city of Victoria, B.C., discharges approximately 85,600 cubic meters (22.6 million gallons) of sewage effluent into the Bight daily (Cokelet, 1995), and because an estimated 10% of the total effluent solids rise to the sea surface in the form of oils and greases (Word et al., 1990), we decided to examine the Bight's near-surface currents. Our primary goal was to use drift cards to infer the fate of the floatable portion of sewage effluent discharged from Victoria's outfalls.

Methods

During the summer of 1997, we released 1,000 drift cards in Victoria Bight, located at the southern end of Vancouver Island, Canada. After consulting engineering drawings supplied by the Capital Regional District (the agency responsible for Victoria's sewage disposal) we chose four release sites: site 1) over the Clover Point outfall; site 2) over the Macaulay Point outfall; site 3) about 400 m east of Albert Head; and site 4) about 650 m northeast of William Head (Figure 1). Sites 1 and 2 were located directly above the diffuser sections of the outfalls, whereas sites 3 and 4 served as statistical control sites.

Using a handheld Magellan Global Positioning System (GPS) unit for positioning, one of us (TJC) released 50 drift cards at each site for a total of 200 cards on five release dates: 19 July; 4 and 17 August; and 6 and 20 September, 1997. Totaled over the five dates, 250 cards were released at each site.

The drift cards were constructed from postcard-sized pieces of thin plywood, painted with non-toxic orange paint. The cards were silk-screened with numbers designating release dates and locations, as well as reporting instructions for beachcombers (including mail and email addresses and a voicemail number).

To analyze the recoveries, we divided the overall region into five recovery zones (Figure 2): 1) San Juan Island vicinity, north of Victoria Bight and eastward into the San Juan Islands; 2) Victoria Bight, from Gonzales Point to William Head; 3) Southwest Vancouver Island, from William Head to Nitinat Inlet; 4) Olympic Peninsula, between Cape Flattery and Dungeness Spit; and 5) Pacific Coast, north and south of Juan de Fuca Strait (Figure 2). With these zones, we performed spatial and temporal analyses of

the recoveries, and compared the coastal recovery data with Ocean Surface CURrent Simulations (OSCURS) an empirical, numerical model of daily Pacific Ocean surface currents.

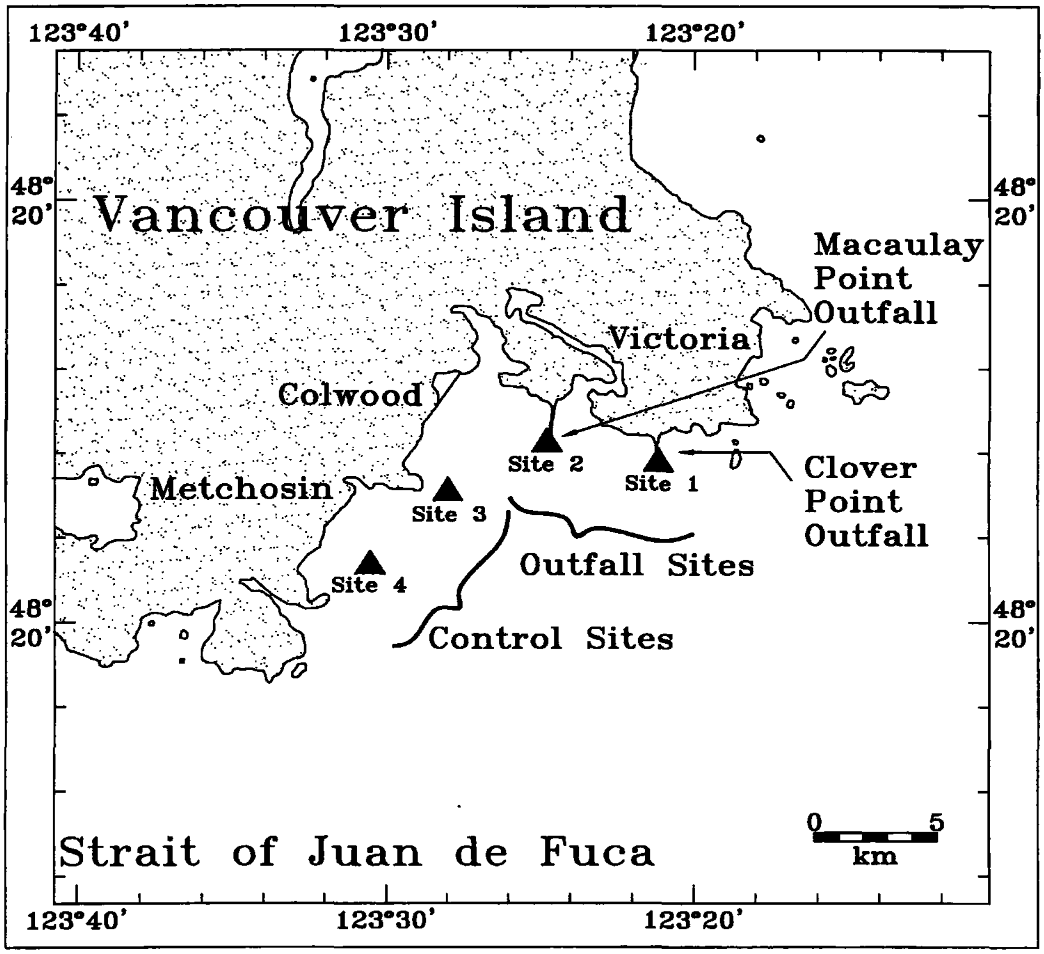

Figure 1. Drift card release sites. Release sites are labeled and marked with solid triangles. The Macaulay Point sewage outfall lies directly under site 2, and the Clover Point outfall lies directly under site 1. Sites 1 and 2 constitute the outfall sites, and

For the spatial analysis, used to determine how cards from each site drifted as a whole, we examined recoveries based on release location. Specifically, we tabulated the cards found according to recovery zone for each release site and used these numbers, along with the total number of cards found from each site, to derive the percentage of cards found in each recovery zone for each release site.

For the temporal analysis, used to determine how the cards were affected by wind and Fraser River runoff, we examined recoveries based on release date. Specifically, we tabulated the cards according to recovery zone for each release and used these numbers, along with the total number of cards found from each release, to derive the percentage of cards found in each recovery zone for each release date. We examined only the cards that exited the Bight because we could not disregard the spatial aspects of card release for cards that did not drift far from their origin. In other words, only for cards that drifted substantial distances (and arrived in the same place) was it possible to disregard the relatively small differences in release location. This may be thought of as the inverse of the butterfly effect. Also, the San Juan Island zone was not included in this analysis because too few cards were found there.

We obtained hourly averages of wind speed and direction, gathered at the Race Rocks lighthouse (Figure 2), from the Atmospheric Environment Service of the Canadian Climate Center. With these we computed daily vector averages to examine the wind patterns during the study period. We obtained daily average Fraser River discharge data for the study period, measured at Hope, British Columbia, from the

Water Survey of Canada.

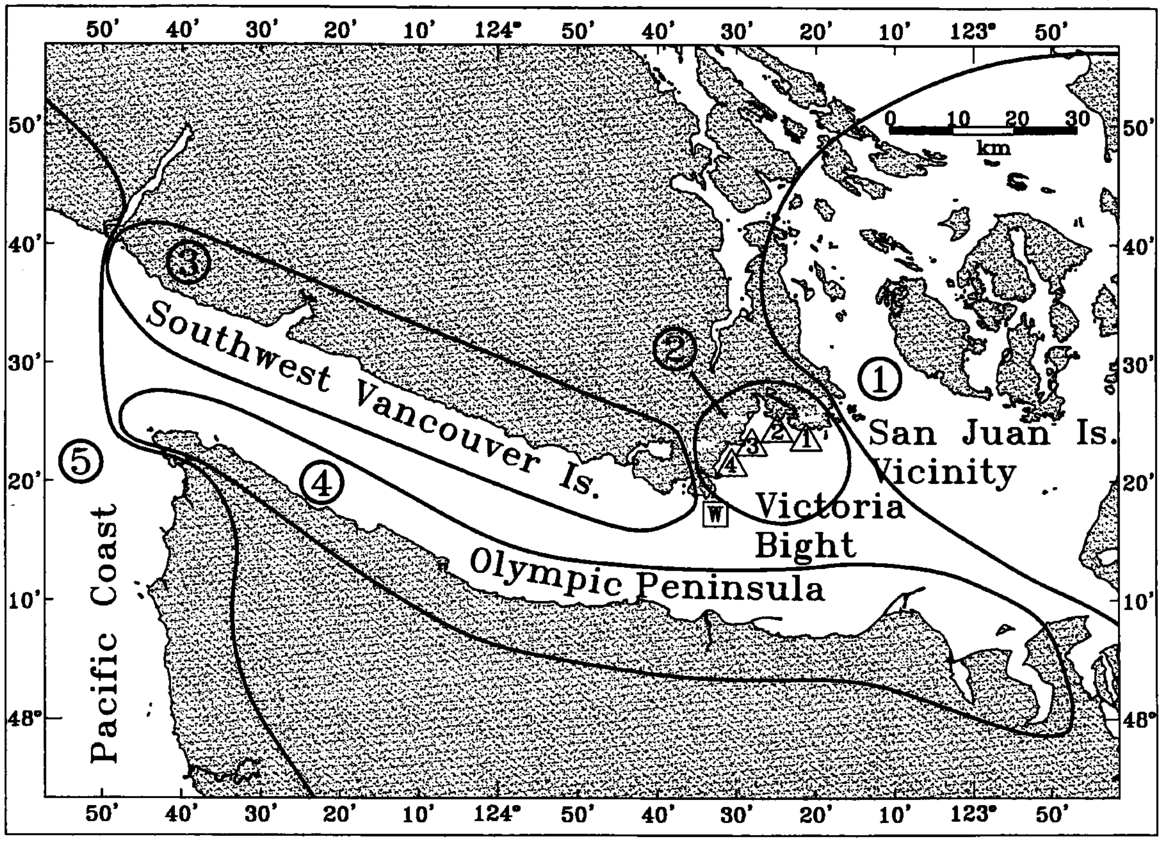

Figure 2. Drift card recovery zones and wind station location. The five recovery zones are labeled and circled. The Victoria Bight zone is comprised of shoreline between William Head and Gonzalez Pt. The San Juan Island vicinity zone incorporates the San Juan Archipelago, Whidbey Island, and Vancouver Island north of Gonzalez Pt. The Olympic Peninsula zone runs from Cape Flattery to Discovery Bay. The Southwest Vancouver Island zone extends from William Head to Nitinat Inlet on the shore of Vancouver Island, and the Pacific Coast zone includes all shoreline outside of the Strait of Juan de Fuca. The Race Rocks wind measurement site is marked with a "W" inside a square.

To examine whether or not drift card recoveries along the Pacific coast reflected dispersal by the prevailing local ocean currents, we used the OSCURS model to track six simulated drifters in the coastal waters of Washington and Vancouver Island OSCURS used empirical formulae, and the ocean-wide gridded daily sea-level pressure data (1946–1998) from the U.S. Navy Fleet Numerical Meteorology and Oceanography Center, to compute the wind-induced component of ocean surface currents in the mixed layer (0–30 m). The daily modeled currents equaled the vector sum of this wind component plus the long-term mean geostrophic current component, computed from long-term mean ocean temperature and salinity fields. OSCURS had been previously calibrated with trajectories of satellite-tracked drifters, and had been found to have a high signal-to-noise ratio (Ingraham, 1997; Ingraham et al., 1998).

Results: Spatial Analysis

The results of the spatial analysis are shown in Table 1. A graph of these percentages versus recovery zone reveals that the drift cards recovered in Victoria Bight were affected by release location more than cards from any other zone (Figure 3). The greatest percentage of cards recovered in the Bight (58.2%) originated from over the outfalls (sites 1 and 2), whereas 31.0% of cards released at site 3, and only 4.7% of cards from site 4, remained in the Bight. Cards found in the southwest Vancouver Island, Olympic Peninsula, and Pacific coast recovery zones had similar percentages by site, but the percentage for each site varied (most likely) according to

the number of cards that escaped Victoria Bight. That is to say, fewer cards from sites 1 and 2 were recovered in these three zones, but fewer cards exited the Bight from these sites.

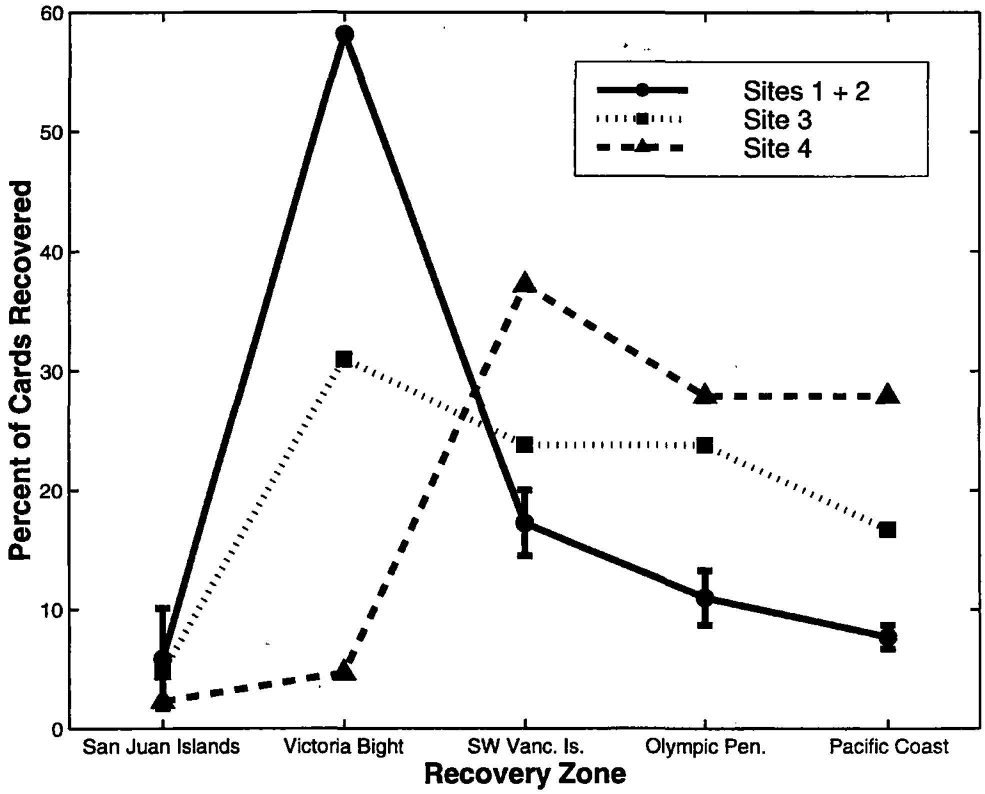

Figure 3. Percentage of drift cards recovered vs. recovery zone. The five recovery zones, from easternmost to westernmost, are listed along the x-axis. Percentages are based on the number of recovered cards from each release site. Data from sites 1 and 2 have been combined and averaged because their values are similar. Error bars have been included to illustrate this similarity.

Table 1. Drift cards released in Victoria Bight analyzed by release site. For each release site, the number of cards released is listed, along with the total percent found, and the percent found within each recovery zone. Numbers given in parentheses denote total number of cards found. We used the total number of cards found from each site to compute the percentages per zone, but used the total number of cards released to compute the total percentage found. For example, of the cards originating at site 1, 40 of the 69 total cards recovered were found in the Victoria Bight zone. Thus, 58.0% of all card recoveries from site 1 were found in the Bight.

			Recovery Zone				
			1	2	3	4	5
Release Site (see Figure 1)	Number Released	Total Found %(#)	San Juan Island Vicinity % (#)	Victoria Bight % (#)	SW Vancouver Is. % (#)	Olympic Peninsula % (#)	Pacific Coast % (#)
Site 1	250	27.6 (69)	10.1 (7)	58.0 (40)	14.5 (10)	8.7 (6)	8.7 (6)
Site 2	250	24.0 (60)	1.7 (1)	58.3 (35)	20.0 (12)	13.3 (8)	6.7 (4)
Site 3	250	16.8 (42)	4.8 (2)	31.0 (13)	23.8 (10)	23.8 (10)	16.7 (7)
Site 4	250	17.2 (43)	2.3 (1)	4.7 (2)	37.2 (16)	27.9 (12)	27.9 (12)

Results: Temporal Analysis

The study bracketed a time period with substantial changes in regional winds and runoff (Figure 4). The wind data reflected the annual transition from summer northerlies to winter southerlies that occurs during fall along the Pacific coast (Ebbesmeyer et al., 1996). At Race Rocks, this transition was from northwesterly sea breezes blowing southeastward through Juan de Fuca Strait in the summer, to variable winds in the fall. The transition occurred between releases 3 (17 August) and 4 (6 September).

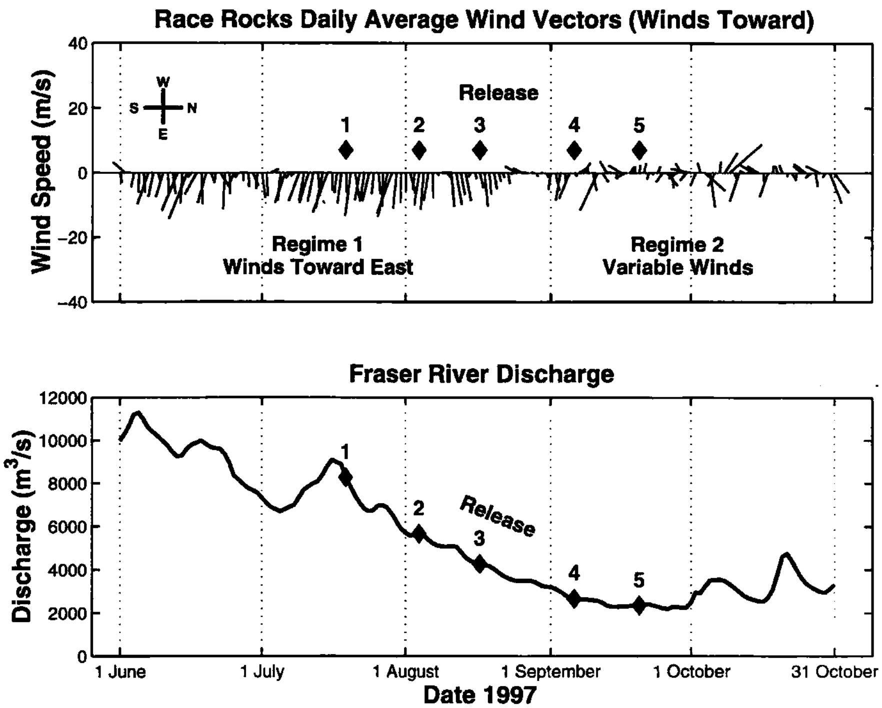

Figure 4. Race Rocks wind vectors and Fraser River discharge. The upper plot shows daily average wind vectors (winds toward) vs. time. For clarity the vectors are oriented with east toward the bottom of the page. Regime 1, northwesterly winds, extends from the beginning of the series through the third week of August. Regime 2, variable winds, begins in late August and extends through the end of the series. The lower plot shows daily average discharge of the Fraser River at Hope, B.C. Releases one through five are marked with a diamond at their respective dates on both plots.

Fraser River discharge also changed dramatically during the study. Daily average flow rates decreased from a June maximum of nearly 12,000 m^3sec^{-1} to ~2,000 m^3sec^{-1} toward the end of September.

The data from Table 2 closely mirrored these changes in winds and runoff (Figure 5). Cards released early in the study were more likely to be flushed to the Pacific coast by the outward flowing current, or be blown to the Olympic Peninsula by the northwesterly winds. As the river input slackened, and the winds became variable, the cards released later in the study tended to collect along the shores of southwestern Vancouver Island.

OSCURS Comparison

Two OSCURS model runs were computed: one during the summer northerly wind regime (17 July to 21 August), and another during the variable wind regime (22 August to 30 September). During the period of northerly winds, the six OSCURS drifters moved steadily southward (Figure 6). During the period of variable winds, simulated drifter movement was variable, with some drifters moving slightly north, and one moving slightly south, but each remaining relatively close to its origin.

Table 2. Drift cards released in Victoria Bight analyzed by release date. For each release date, the number of cards released is listed, along with the total percent of all releases found, and the percent of all recoveries found within each recovery zone. Numbers given in parentheses denote total number of cards found. We used the total number of cards found from each release to compute the percentages per zone, but used the total number of cards released to compute the total percentage found. For example, of the cards released 19 July, 16 of the 54 cards found were found in the Pacific Coast zone. Thus 29.6% of cards from the first release were found on the Pacific coast.

			Recovery Zone		
			3	4	5
Release Date (1997)	Number Released	Total Found %(#)	SW Vancouver Is. %(#)	Olympic Peninsula %(#)	Pacific Coast %(#)
19 July	200	27.0 (54)	9.3 (5)	33.3 (18)	29.6 (16)
4 August	200	24.5 (49)	12.2 (6)	16.3 (8)	18.4 (9)
17 August	200	16.5 (33)	9.1 (3)	18.2 (6)	3.0 (1)
6 September	200	14.5 (29)	48.3 (14)	0.0 (0)	0.0 (0)
20 September	200	24.5 (49)	40.8 (20)	8.2 (4)	6.1 (3)

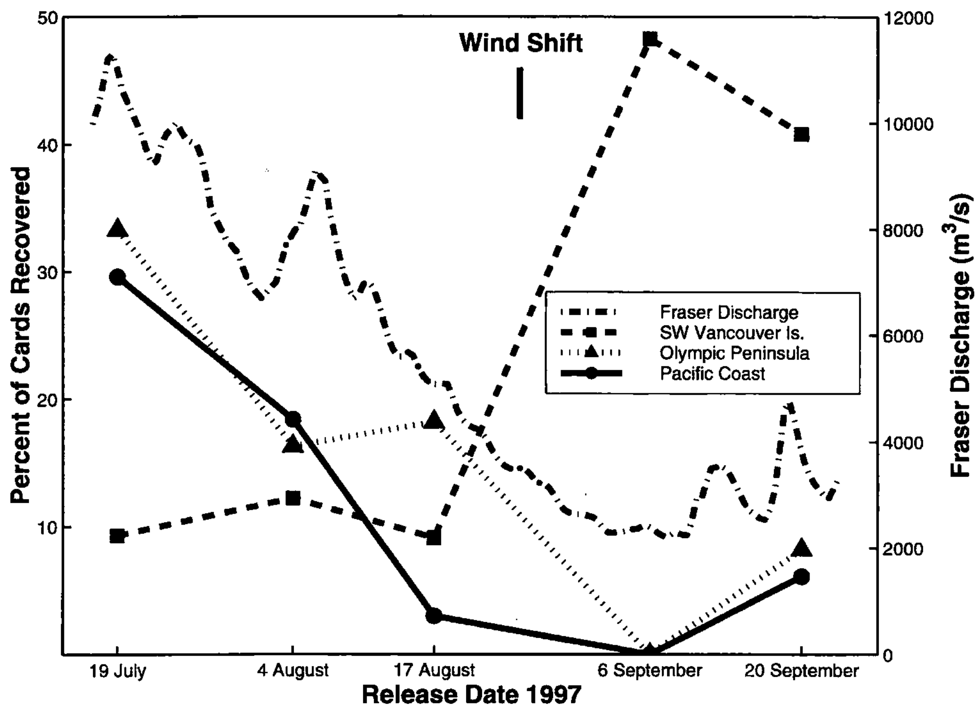

Figure 5. Percent of drift cards recovered vs. release date. The five release dates are listed along the x-axis. The three lines with data markers (squares, circles, and triangles) denote cards recovered in the three analyzed zones. Percentages are based on the number of recovered cards from each release date. Also shown on this graph is the Fraser River discharge, along with the approximate time of the wind regime shift that occurred in late August.

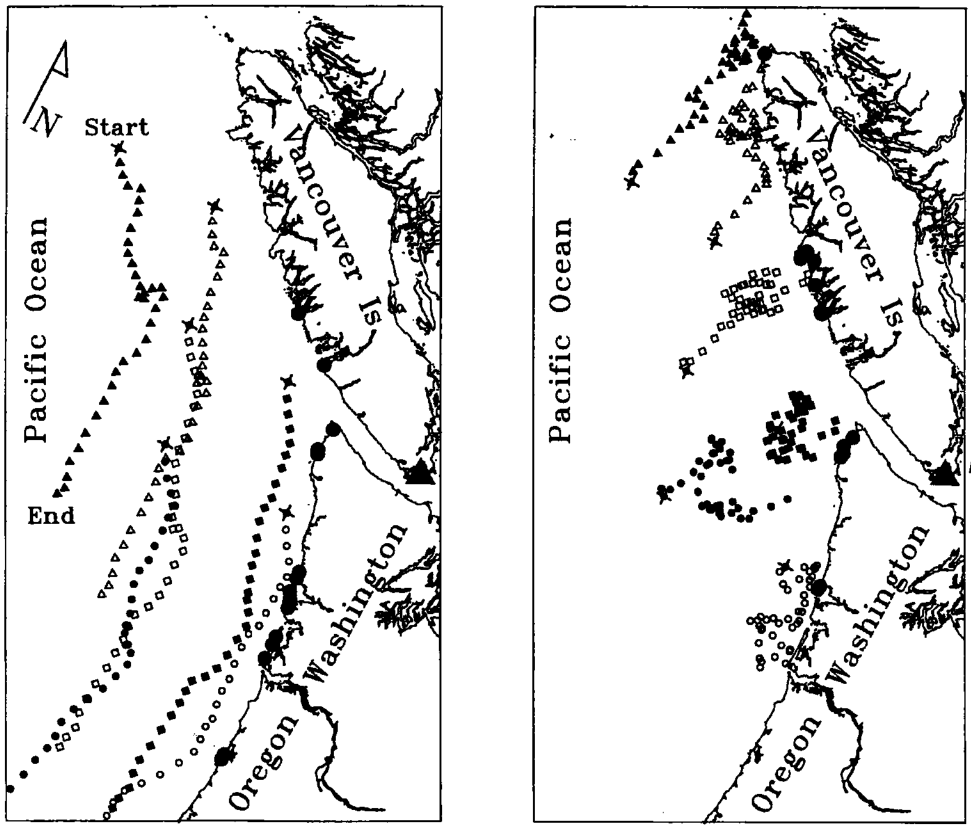

Figure 6. OSCURS model drifter trajectories vs. actual Pacific coast recoveries. Left panel: model drifter trajectories based on atmospheric pressure measurements for 17 July through 21 August, 1997. Also shown are Pacific coast recoveries of drift cards released in July, 1997. Right panel: model trajectories for 22 August through 30 September, 1997. Also shown are recoveries of cards released in August and September. The drift card recoveries in both panels are marked with solid circles along the Pacific coast. The six simulated drifters originated from the points marked by "X." All drift cards originated from the location at the southern tip of Vancouver Island marked by a solid triangle.

The drift cards found on the Pacific coast were distributed in the same pattern. Of the cards released during July, two were found north of the Strait on Vancouver Island, whereas 14 were found south of the Strait on Washington shores. Of the cards released during August and September, seven were found north, and six were found south.

Discussion

During the analysis we sought to answer four questions, the first being, "Did cards released at different sites end up in different locations?" When considering whether or not cards will leave the Bight, the answer is yes. Cards released over the outfalls had almost twice the likelihood of being found in Victoria Bight as cards released at site 3. Compared to cards from site 4, cards from sites 1 and 2 had about 12 times the likelihood of being found in the Bight. However, differences in recoveries for other zones appeared to be related to the differing number of cards that escaped the Bight from each site. Thus, we believe discharge location greatly affected the short-term fate of drift cards in Victoria Bight.

The second question, "Did cards released at different times end up in different locations?" could only be applied to three of the five recovery zones. Release location must be considered when dealing with the Victoria Bight zone, thus complicating this question beyond the scope of our study. The San Juan Island zone could not be analyzed due to lack of data. For the other zones—southwest Vancouver

Island, Olympic Peninsula, and Pacific coast—the answer is yes. Differences in wind and river discharge appeared to affect the long-range fate of drift cards.

The third question, "How do these data compare to predicted data?" was addressed with the OSCURS model of Pacific Ocean currents. When compared to Pacific coast drift card recoveries, OSCURS increased our confidence in the drift card data. Cards subjected to summer conditions were recovered predominantly in the south, as predicted by OSCURS. OSCURS predicted variable currents in the fall, during which time card recoveries were distributed evenly north and south. The OSCURS-simulated drifters confirmed that drift card recoveries correlate with coastal surface currents.

Finally, we returned to our initial question, "Where does floatable sewage from Victoria's outfalls go?" The data suggest that roughly 60% is trapped in the Bight, probably due to nearby tidal eddies (Ebbesmeyer et al., 1991). The remaining 40% is dispersed widely, mainly along the Pacific coast, and on both sides of Juan de Fuca Strait. Furthermore, the data suggest that if the outfalls were located in the vicinity of sites 3 and 4, off Albert Head and William Head, flushing of floatable sewage from Victoria Bight may be significantly improved. This not being the case, the ultimate fate and concentration of the floatable sewage trapped in Victoria Bight should be the subject of further research.

Acknowledgements

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Possible Impacts of Tidal Refluxing on Southern Puget Sound Benthos

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Introduction

We were motivated by 20 years of class projects at Shoreline Community College in which the sediments at 488 stations throughout Puget Sound were sampled and analyzed (1976 – 1996). Regional survey maps showing the ratio of empty benthic shells to those containing live specimens, drew our attention (Figures 1, 2, and 3). *Psephidia lordi*, for example, an important food item for English sole, was commonly found living north of the Tacoma Narrows, but in Southern Puget Sound was evident primarily as empty shells (Figures 2 and 3). In this paper, we explore the hypothesis that Southern Puget Sound's unique circulation produces this benthic anomaly.

A cursory oceanographic inspection placed Southern Puget Sound in regional perspective. Consider the rate at which upwelled water cycles through Puget Sound. The upwelling time scale of a given water body may be expressed as $T = V/Q$, where V is the basin's volume, and Q is the horizontal transport which upwells in the vicinity of mixing zones (Table 1).

The resulting time scale (10 days; Table 1) is the interval in which the South Sound's deeper water upwells into its upper layers. Since much of the upper layer lies within photic zone, refluxing rapidly raises deep, nutrient-rich water into shallow depths where plankton grow. Though Southern Puget Sound contains only 9% of the Puget Sound's overall volume, its waters are more highly refluxed than in any other major Puget Sound subdivision (Main Basin, Whidbey Basin, Hood Canal). Therefore, South Sound appears to us as an archipelago of interconnected water bodies with a unique collective behavior.

Table 1. Upwelling time scales (T) for Puget Sound basins. The regions have been ordered by time scale. Notation: the upwelling scale $T = V/Q$ (see text); and B, C, D, E, denote regions and associated volumes computed by McLellan (1954). Transport estimates are from Cokelet et al. (1990).

Puget Sound Region	Upwelling Time Scale (T, days)	Volume (V, km^3)	Upwelling Transport (Q, m^3/s)
Southern Puget Sound (C)	10	16	20,000
Main Basin (B)	60	77	15,000
Whidbey Basin (E)	110	29	3,000
Hood Canal (D)	120	25	2500

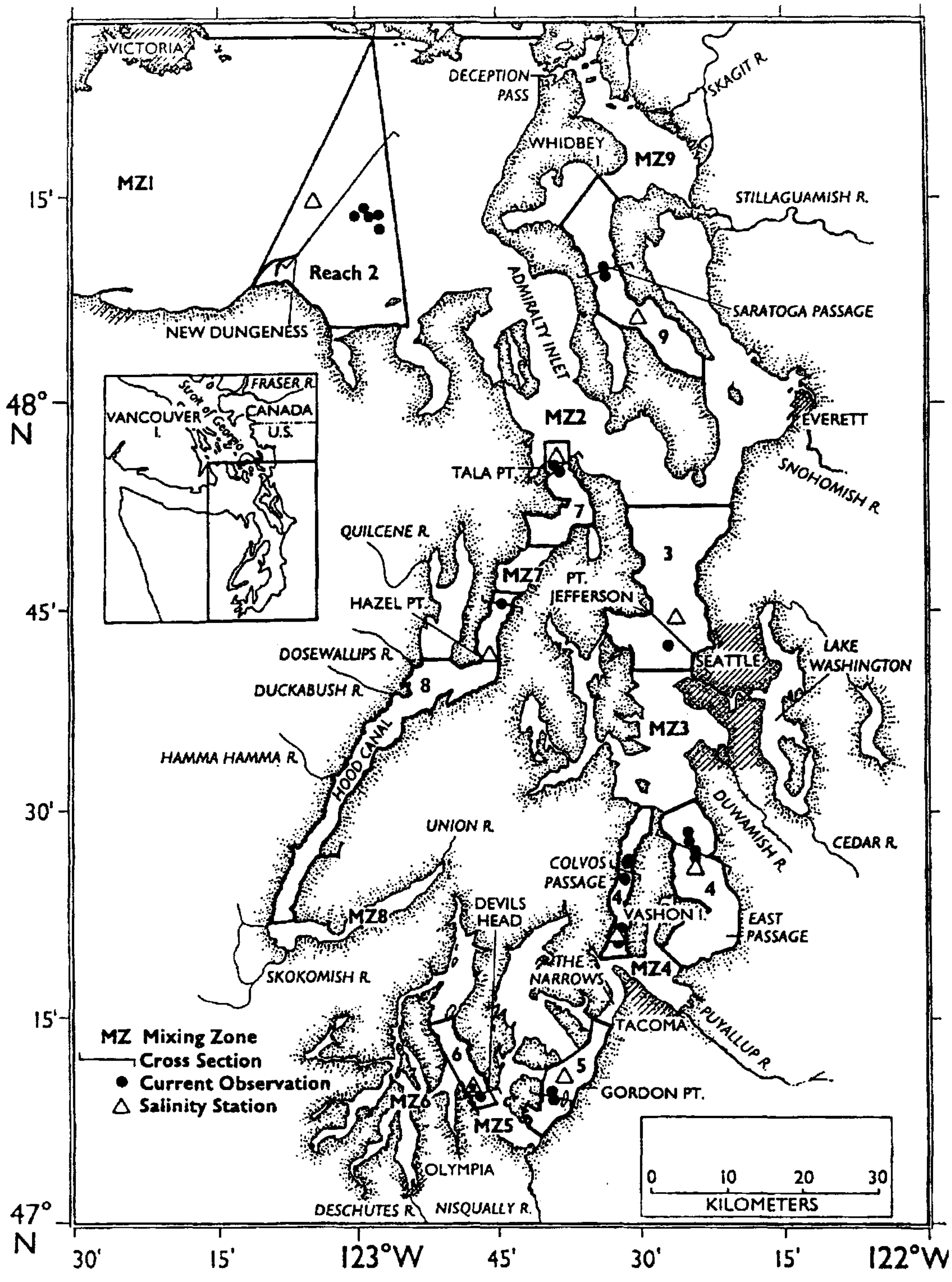

Figure 1. Reaches and mixing zones of the Juan de Fuca Strait/Puget Sound estuary (from Cokelet et al., 1991). Bold outlines denote reaches; mixing zones are labeled MZ. See Figure 2 for a 3-D view of the Sound's circulation.

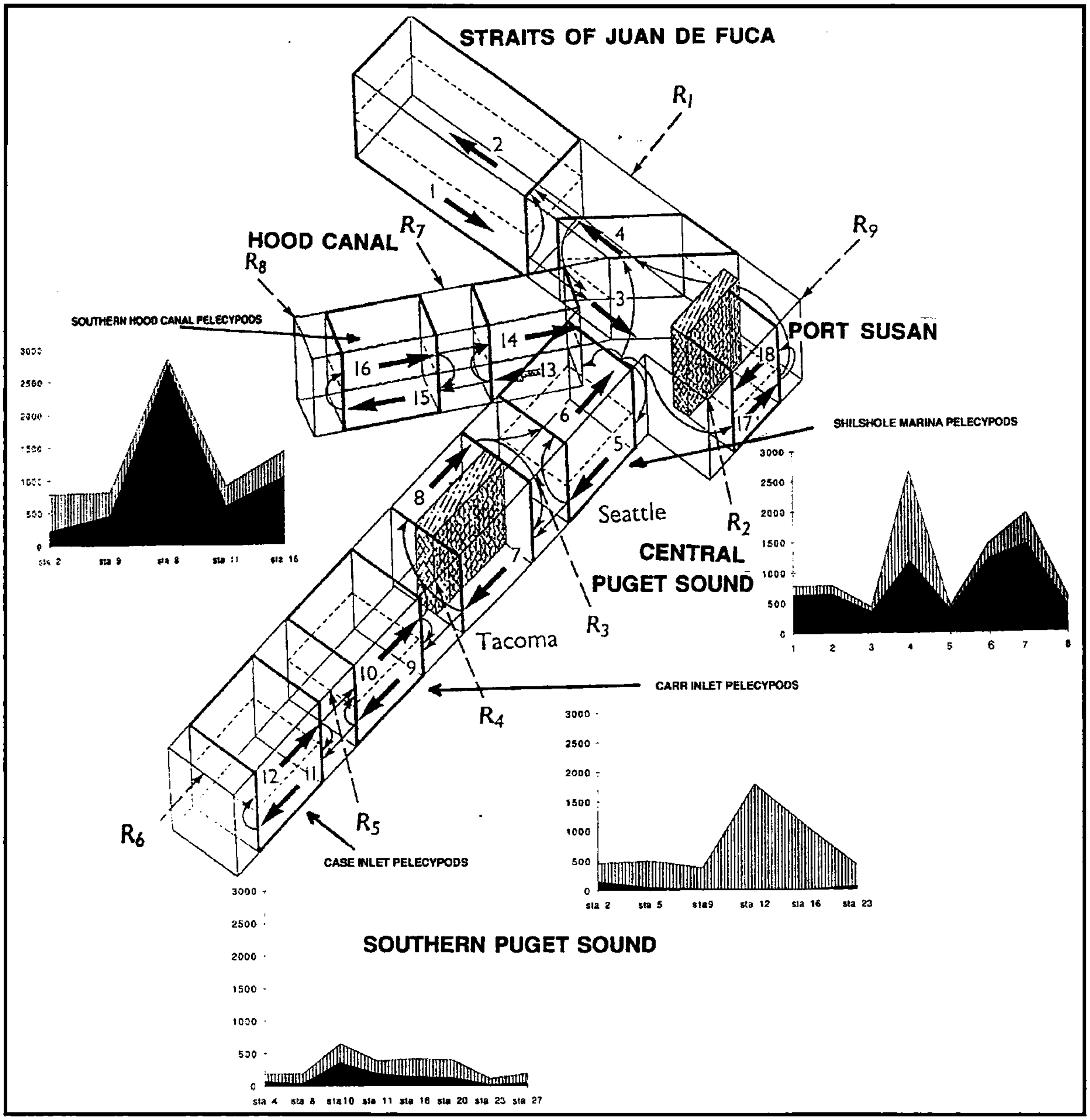

Figure 2. Puget Sound circulation compared with benthic shells. The circulatory schematic indicates flow direction in the 18 layers comprising Puget Sound (from Cokelet et al., 1991). See Figure 1 for locations of the flow reaches 1-18. Inset panels show numbers of empty shells and live pelecypod specimens at stations from benthic surveys conducted by Shoreline Community College in four areas: southern Hood Canal; Shilshole Marina in the Main Basin; and Carr and Case Inlets in southern Puget Sound. Note that compared with the Main Basin and Hood Canal, most of the shells in southern Puget Sound were empty.

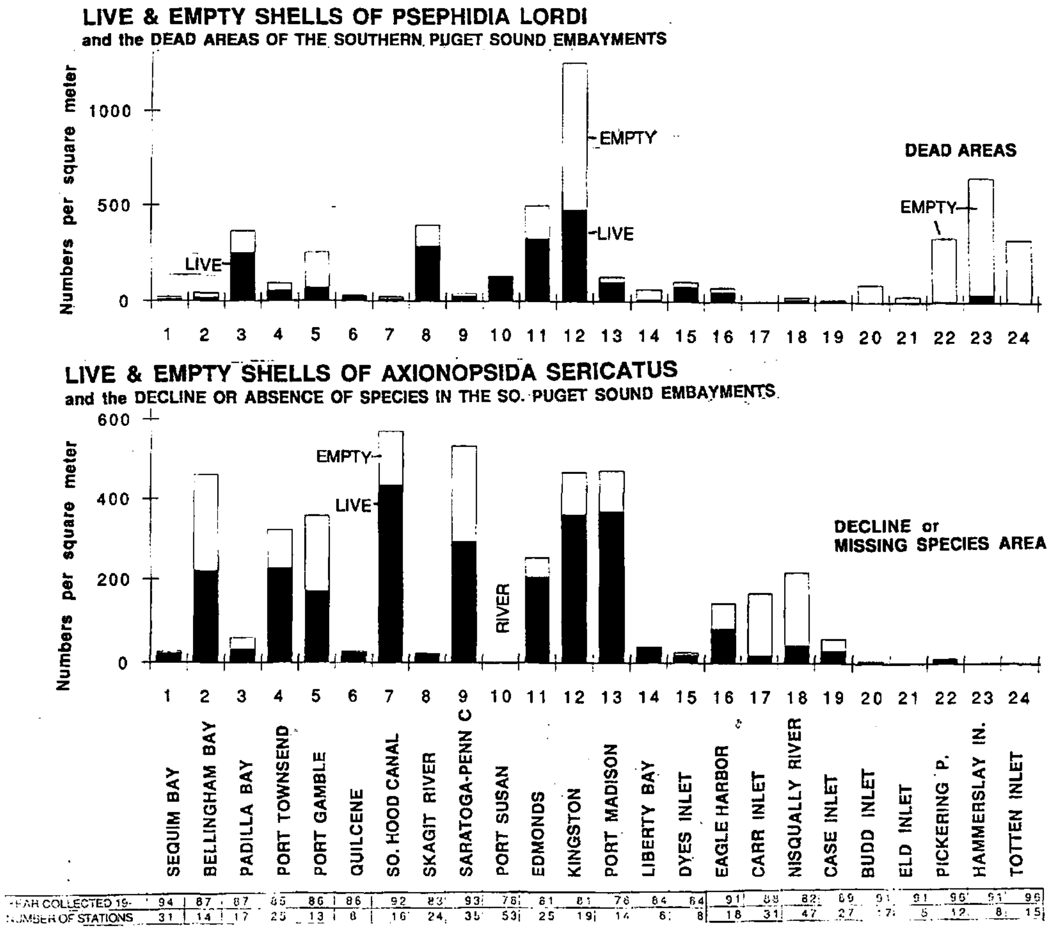

Figure 3. Live and empty shells from benthic surveys (*Psephidia lordi, Axionopsida sericatus*). Each bar represents the average number of live specimens (darkened) and empty shells (open) found in a given survey. The 24 areas surveyed and associated numbers of benthic stations, are provided at bottom (please consult Puget Sound atlases for locations). The bars are laid out approximately along the main axis of the Juan de Fuca Strait/Puget Sound estuary with the following area groupings: areas 1–4, Juan de Fuca Strait and approaches; 5–7, Hood Canal; 8–10, Whidbey Basin; 11–16, Main Basin; 17–24, Southern Puget Sound. Note the marked drop off in fish food abundances of *P. lordi* and *A. sericatus* south of the Narrows.

Methods

Benthic samples

Benthic samples obtained in 24 surveys during 1976 –1996 were examined. These surveys were designed to sample benthic species in the deeper waters and not the intertidal areas. Please consult Puget Sound atlases for locations of the many places surveyed.

The samples were collected with a 0.1-m^2 van Veen grab sampler and washed through a 1-mm screen. Washed residues were preserved in a 10% formaldehyde solution using rose bengal stain. Within days after each survey, the samples were sorted under a magnifying lamp by taxa and preserved with a glycerin-alcohol solution. While sorting, the number of empty whole shells was estimated as half of the umbo portion of the pelecypods (umbo: elevated knob near the ligament on each valve of a bivalve). The numbers of live and empty shells of all pelecypods were enumerated.

Refluxing

The Puget Sound Refluxing (PSR) model represents Puget Sound as a network of advective reaches linked by mixing zones (Figures 1 and 2). Within the mixing zones, reflux parameters determine the distribution of the inflowing water into the outflowing reaches. The model has been successfully applied to explain the changes in observed copper concentrations that resulted from improved sewage treatment in the 1980s (Paulson et al., 1992).

Synthesis

The network of reaches and mixing zones, together with the refluxing between adjoining reaches, determines the distribution of salt and fresh water within Puget Sound. By combining historical observations of currents, salinity, and freshwater inputs, estimates of the transport and transit times were determined for each of the 18 reach layers comprising the PSR model (Figures 1 and 2; Cokelet et al., 1990). The observed salinities were then used to compute reflux coefficients for each of the layers feeding into a given mixing zone. In addition, transit times for the mixing zones were computed based on the zone's volume and associated transports.

Although the PSR model is based on long-term averages, and does not specifically address time-varying processes, the transit times and transports do provide time scales for the flushing of chemicals introduced into Puget Sound. Specifically, the transit time, volume transport, and reflux parameters may be mathematically combined to estimate both the amount flushed from a given region and that remaining after the introduction of a tracer at a given location.

Because Puget Sound contains multiple mixing zones wherein a portion of the outflowing surface layer is refluxed back into the system, there are numerous pathways between given locations. If we represent Puget Sound as a set of simultaneous equations, we may solve them for the concentrations measured at the exit of each of layer as a time-varying quantity that depends on the concentrations in the source layers. By solving 18 equations for each time step, the effect of the transport processes in distributing input throughout the Sound may be computed.

Flushing and Retention

The question is often asked: "How long will it take to flush the material from the Puget Sound system?" Given that introduced material will be refluxed throughout the Sound's reaches, and the degree of refluxing varies with location, "flushing" times may be defined in several ways. In this paper we focus on two definitions, each dealing with the response of the Sound to a conservative tracer introduced at a steady rate over a period of three days. Since the time scales of the individual reaches vary between approximately 10 to 20 days, and the scale of the system is about 100 days, in practical terms, this input is an "impulse."

The first definition is a Puget Sound-wide flushing time. It is the interval required to remove material from Puget Sound by transport to the Pacific Ocean from Juan de Fuca Strait. Figure 4 shows the times for the impulse to be removed from four different reaches. The first site is the surface layer at Point Jefferson, which receives the effluent discharged from the Metro/King County West Point outfall. It flushes the most quickly of all, with 50% of the material removed after approximately 90 days.

The second site is in Colvos Passage. Its flushing is similar to that from the Point Jefferson site, except its response lags that of the Elliott Bay/Alki Point mixing zone, and a small amount of Colvos Passage material refluxes into East Passage. The third site is the lower (inflowing) reach at Devils Head within Southern Puget Sound. It can be seen that both the Colvos Passage and Devils Head reaches require about 120 days before 50% of the material is removed via transport out Juan de Fuca Strait. The fourth site is the lower reach of the inner arm of Hood Canal, which is labeled Hazel Point in the PSR model. Hood Canal is widely understood to be the slowest-responding branch of Puget Sound, and Figure 4 supports this hypothesis.

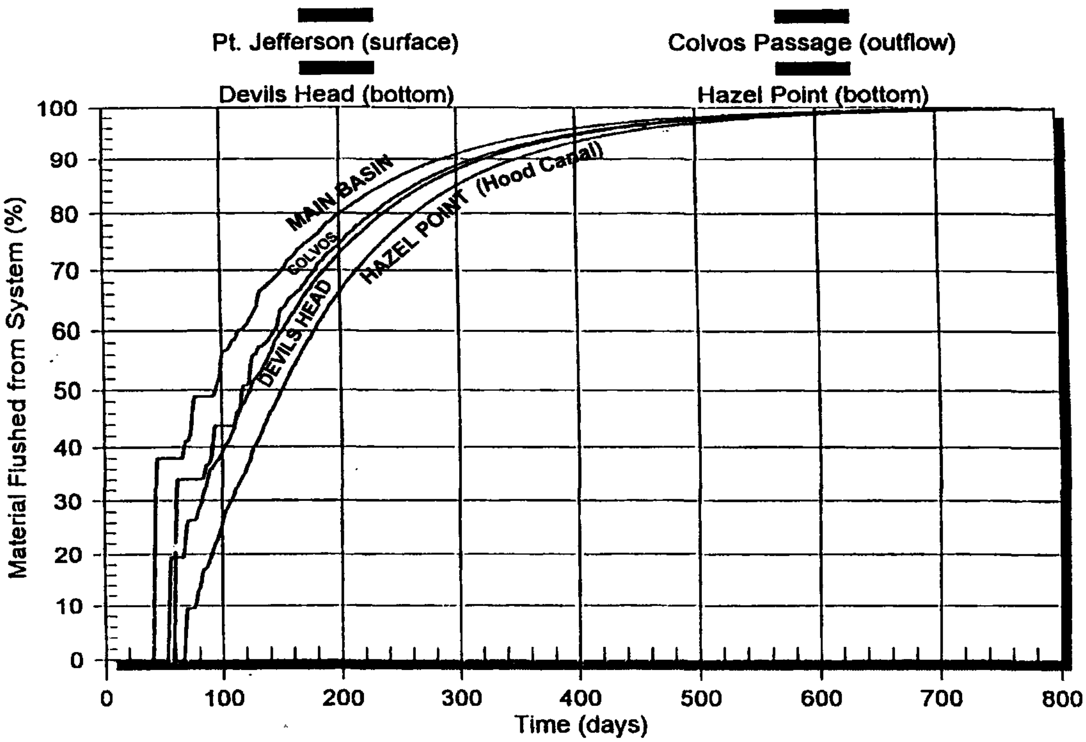

Figure 4. Flushing of a three-day step input from four areas of Puget Sound. Comparison of alternate input locations.

The second flushing definition deals with the amount of time required to remove the material from the branch of Puget Sound in which the material is introduced. This flushing is complicated by the inland refluxing of material. For the Point Jefferson site, the relevant measure is the amount of material that remains within the Puget Sound system including the input site, the lower layer reach beneath the input site, and the three pairs of reaches extending southward to Devils Head. The measure used for the Devils Head input involves the material retained inland of the Tacoma Narrows and thus includes the Gordon Point and Carr Inlet regions. The Hood Canal site is characterized by material retained in the Hazel Point reaches. The Colvos Passage input site was also investigated; for clarity it is not included in Figure 5.

A striking aspect of Figure 5 is the large amount of material retained in Southern Puget Sound for releases in the Devils Head reach. It can be seen that 20 days after the introduction of the conservative tracer, the model predicts 50% of the material will be retained in the Gordon Point-Carr Inlet area and Devils Head reaches. The amount of material drops off to 14% at 50 days and decays exponentially thereafter. In contrast, if the material is introduced in the upper layer at Point Jefferson, it is quickly transported into the Admiralty Inlet mixing zone, and thereafter the total material returned to the inland reaches never exceeds about 31% of the initial dose.

The comparison shown in Figure 5 is more striking if we consider the water volume in which the material may be dispersed. The 31% retention at Point Jefferson is distributed over all the Main and Southern Puget Sound basins, whereas the material retained from the Devils Head site is dispersed only over the finger inlets. McLellan (1954) lists the volume of the Main Basin at 12.1 cubic nautical miles (76.9 cubic km) and that for Southern Puget Sound as 2.5 cubic nautical miles (15.8 cubic km.) The divisor for the Point Jefferson discharge is therefore 14.6 cubic nautical miles versus 2.5 for Devils Head.

Thus, the Southern Puget Sound region differs from the Main Basin in both the quickness with which the lower layer waters are refluxed into the upper layers, and in the relative slowness of the removal process.

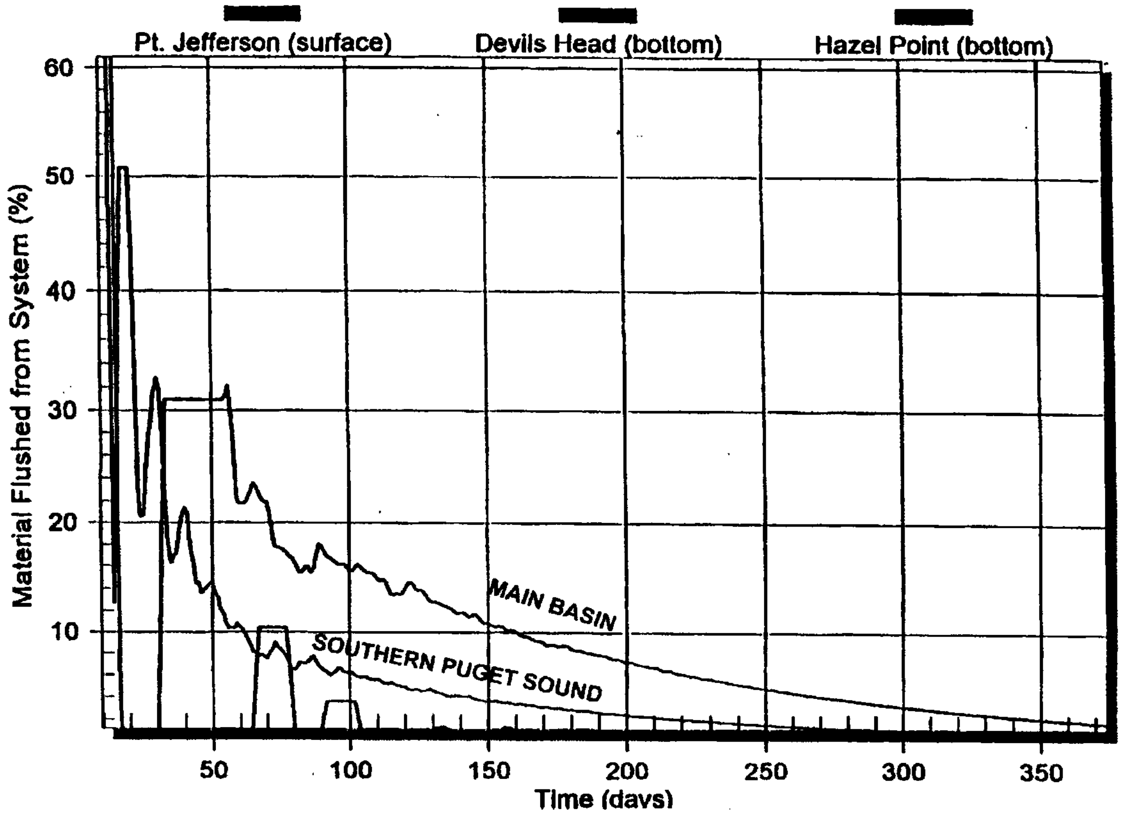

Figure 5. Retention of a three-day step input from three areas of Puget Sound. Comparison of alternate input locations.

Refluxing Model and Benthic Biology

Pelecypod counts of living and empty specimens north of the Tacoma Narrows sill typically have higher numbers of living to empty shells than those of Southern Puget Sound (Figures 2 and 3). Shilshole Marina samples, where sediments contain high concentrations of oil and metal debris, have greater live counts and a more diverse fauna than those of the Southern Puget Sound. Even in the southernmost portions of Hood Canal, subtidal sediments exhibit comparatively high live-to-empty shell ratios, as well as many species absent in South Sound.

Previously, Harman and Serwold (1977) found that, based on the benthic foraminiferal distribution, the sills in Admiralty Inlet blocked the deep water organisms of Juan de Fuca Strait from entering the Main Basin (e.g., *Cassidulina californica, C. reflexa)* or significantly reduced their concentrations (e.g., *Uvigerina juncea, Globobulimina auricula, Epistomenella pacifica).* Sediment cores obtained by Dr. Fred Nichols from mid-channel off West Point contained none of Juan de Fuca Strait species. Furthermore, the pectinarians which Nichols began studying in the 1970s were no longer present in the 1990s.

The sensitivity of benthic organisms to degraded sea bottoms in Southern Puget Sound shows similar trends to that of the Puget Sound salmon pen farms located at varying distances from Juan de Fuca Strait. The more oceanic-influenced Skagit Bay fish farm contains many of the shallow water mud-loving species (e.g., *Ascila castrensis, P. lordi* and *Axionopsida sericatus.* These species are absent in the more impacted southern farms or basins (Figure 3).

The sensitivity of *A. sericatus* and *P. lordi* is illustrated in the decline in their concentration toward the pen edge and most significantly in their decline and present-day absence from the farms (Figure 6). Perhaps the difficulty in maintaining their population is associated with their brooding mode of

reproduction, which may make recruitment by pelagic larvae impossible. Some pelecypod species—such as *Mysella tumida* and *Parvulucina tenuisculptus*, which also dominate the less diverse benthic faunas of the deep Southern Puget Sound basin—respond favorably to the salmon pen organic loading of bottom sediments.

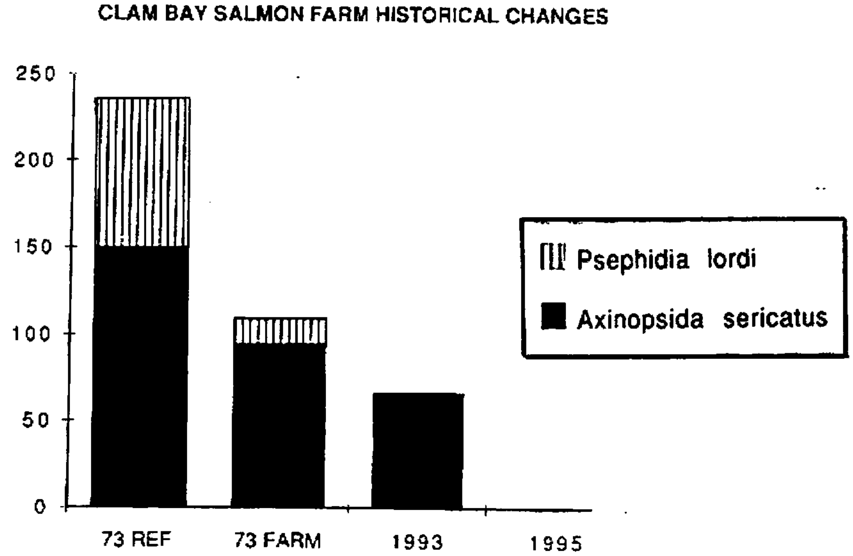

Figure 6. Historical changes in live concentrations of *Psephidia lordi* and *Axionopsida sericatus* over Clam Bay salmon pen sites. Data from Mahnken (1993) and Brooks (1992, 1995).

Unpublished Shoreline Community College analyses indicate significant declines in other species south of the Tacoma Narrows, as well as reductions in nearshore species such as the ostracod *Euphilomedes spp*, and the sedentarian polychaete *Phyllochaetopteran prolifica.* This polychaete forms chitinous worm tubes which provide substrates for tunicates, sponges, foramninifera, scallops, and sea cucumbers. Mahnken (1993) indicated their dominance at his reference site but described their absence and presence as empty tubes at a former fish farm site. These polychaetes have not yet returned to the Clam Bay farm site.

The organic loading at the salmon pens obviously impacts areas beyond the "200-foot Reference Site" based on the abnormal dominance of *Capitella capitata* for tidal channel habitats. Strong currents in Rich Passage could transport the same organics that cause the farm declines into adjacent depositional sites of Yukon Harbor where *A. sericatus* occurs. This is suggested by rock-attaching arenaceous foraminifera, *Trochammina carlottensis,* present in Rich Passage that are dispersed into Yukon Harbor as well as being the ultimate settling site for the pelagic diatom, *Coscinodicus spp.*

The refluxing of river sediments is expected to cause greater sedimentation due to longer residence times. This phenomenon appears to be exemplified by lower-sediment concentrations of the pelagic diatoms *Coscinodiscus spp* in Port Susan (less than 50 frustules/ gram sediment) compared with those in the Main Basin and Hood Canal (greater than 200 frustules/gram sediment). The strong currents in tidal channels or sill areas such as Rich Passage, Colvos Passage, Tacoma Narrows and Nisqually Reach result in concentrations less than 5 frustules/gram sediment compared with nearby depositional sites. Thus, suspended and sea bottom debris is transported by currents creating organic-rich sediment.

Conclusion

We struggled to unite physical refluxing and benthic ecology because the collective data suggested to us that South Sound's high level of refluxing is recycling introduced materials, which in turn impact the benthos south of the Tacoma Narrows. Despite our efforts, it is not known whether retention effects associated with refluxing are significant. Longer exposures to pollutants due to slower flushing in

Southern Puget Sound may negatively affect benthic populations. Given the distressed condition of selected benthic populations suggested by the Shoreline Community College benthic surveys, future studies should address the underlying toxicological reasons for these declines, particularly concerning the dispersal of brooding benthic species.

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We thank the many Shoreline Community College Marine Science Technical Program students who participated in the field surveys and painstakingly sorted the benthic samples, and Suzanne Giles, Evans-Hamilton, Inc., for helpful comments.

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Siting of Large Municipal Wastewater Outfalls in Central Puget Sound: What Does Society Need to Know to Minimize the Impact of Wastewater Discharges on Puget Sound and How Can Puget Sound Scientists Answer these Questions?

Randy Shuman
King County Department of Natural Resources

Abstract

The next five years may bring the siting of one or more large municipal wastewater outfalls in central Puget Sound, potentially in both northern King County and Snohomish County. These facilities may be necessary in response to growth in these areas. The decisions made on siting these outfalls will impact the water quality in Puget Sound for the next century.

- What information can and should Puget Sound scientists provide to environmental managers and elected officials to ensure that these outfalls will have the minimum impact on Puget Sound ?
- Does our present permitting and siting process efficiently accomplish the goals of siting these outfalls for minimum impact and effective operation ?
- Do we know enough to look at Puget Sound as a system when siting wastewater outfalls, rather than siting each outfall individually as has been done in the past ?

PUGET SOUND RESEARCH '98

SESSION 2B

TOXIC CONTAMINANTS

Session Chair:
Sheri Tonn
Pacific Lutheran University

Differences in the Concentrations of Priority Pollutant Metals in Seawater Samples from Puget Sound and the Strait of Georgia

Eric Crecelius and Valerie Cullinan
Battelle Marine Sciences Laboratory

Introduction

The Washington State Department of Ecology (WDOE) requires industrial discharges to determine the concentrations of relevant metals in receiving water as part of the process for renewing wastewater discharge permits. These concentrations of metals in receiving water are considered in establishing environmental protective discharge limits. The study reported here was conducted to determine the concentrations of 13 U.S. EPA priority pollutant metals in surface seawater of three regions of Puget Sound. The seawater samples were collected and analyzed using new "clean metals" methods EPA has drafted for measuring the concentrations of ambient metals in seawater with detection limits in the range of 0.0002 to 0.3 µg/L. The results reported here are the only known data on regional concentrations of several metals in Puget Sound.

Methods

The three regions included Cherry Point, northwest of Bellingham in the Strait of Georgia only 16 km from Canadian waters; March Point near Anacortes, at the eastern edge of the San Juan Islands; and Commencement Bay, the industrial harbor in Tacoma. At each region a grid of 10 stations was sampled once in the summer of 1997. The grid covered an area approximately 3 by 6 km. The sampling stations were selected to minimize the influence from local point sources, such as outfalls, rivers, and marinas. The location of the stations was determined by a global positioning system (GPS) and the coordinates are given in Tables 1–3.

Table1. Results for conventional water properties - Cherry Point stations, sample date: July 16, 1997

Station #	North Latitude	West Longitude	Temp. (°C)	pH	TSS (mg/L)	Salinity (ppt)
CP 1	48° 52.3479 N	122° 47.357 W	16.0	8.18	0.800	18.6
CP 2	48° 52.2295 N	122° 46.7617 W	16.5	8.13	1.07	18.8
CP 3	48° 51.1480 N	122° 47.9152 W	17.0	8.14	1.20	18.3
CP 4	48° 51.0656 N	122° 46.4797 W	16.5	8.08	0.933	19.4
CP 5	48° 49.9481 N	122° 45.9158 W	16.1	8.03	1.07	18.0
CP 6	48° 49.5052 N	122° 46.7361 W	17.3	8.00	2.13	17.3
CP 7	48° 49.3868 N	122° 44.6598 W	17.2	7.99	0.933	18.2
CP 8	48° 48.4752 N	122° 45.6082 W	16.7	8.18	0.400	20.4
CP 9	48° 48.9130 N	122° 43.7114 W	17.8	8.15	1.60	19.5
CP 10	48° 48.1353 N	122° 43.7883 W	16.7	8.07	1.07	19.1
	mean		16.8	8.10	1.12	18.8
	standard deviation		0.555	0.0714	0.467	0.883

Table 2. Results for conventional water properties - March Point stations, sample date: June 30, 1997

Station No.	North Latitude	West Longitude	Temp. (°C)	pH	TSS (mg/L)	Salinity (ppt)
MP 1	48° 32.5880 N	122° 33.8639 W	13.6	7.94	2.00	25.6
MP 2	48° 31.9082 N	122° 33.8349 W	13.1	7.96	1.60	27.4
MP 3	48° 31.6507 N	122° 36.5017 W	11.5	7.87	1.87	28.8
MP 4	48° 31.6130 N	122° 35.4594 W	11.6	7.88	2.27	28.3
MP 5	48° 31.5117 N	122° 34.7710 W	12.2	7.88	2.13	28.4
MP 6	48° 31.4859 N	122° 33.5712 W	13.8	7.96	2.27	27.4
MP 7	48° 31.0739 N	122° 35.0702 W	12.4	7.93	2.80	28.3
MP 8	48° 31.1254 N	122° 34.2370 W	12.0	7.90	3.73	28.6
MP 9	48° 30.9967 N	122° 33.5326 W	13.8	7.96	2.00	27.2
MP 10	48° 30.6619 N	122° 32.9889 W	14.5	8.02	1.73	27.6
	mean		12.9	7.93	2.24	27.8
	standard deviation		1.05	0.0476	0.621	0.945

Table 3. Results for conventional water properties - Commencement Bay stations, sample date: July 11, 1997

Station No.	North Latitude	West Longitude	Temp. (°C)	pH	TSS (mg/L)	Salinity (ppt)
CB1	47° 17.4981 N	122° 26.2301 W	13.5	7.78	4.13	27.0
CB2	47° 17.4054 N	122° 25.4101 W	15.7	7.79	3.07	25.3
CB3	47° 17.0965 N	122° 26.8007 W	13.2	7.80	7.33	26.5
CB4	47° 16.9523 N	122° 26.0544 W	13.8	7.79	2.40	27.4
CB5	47° 17.2406 N	122° 24.8263 W	16.5	7.78	2.53	22.2
CB6	47° 16.9574 N	122° 25.2854 W	14.9	7.79	2.53	26.0
CB7	47° 16.7257 N	122° 25.6520 W	13.5	7.76	3.20	27.6
CB8	47° 16.5094 N	122° 26.6760 W	13.6	7.75	3.87	27.1
CB9	47° 16.3703 N	122° 26.0865 W	12.8	7.78	16.0	27.9
CB10	47° 16.0678 N	122° 26.4984 W	14.3	7.75	6.00	27.3
	mean		14.2	7.78	5.11	26.4
	standard deviation		1.18	0.0177	4.15	1.68

The sampling procedures were from the EPA Method 1669: Sampling Ambient Water for Trace Metals at EPA Water Quality Criteria Levels (EPA 1996c). The sampling procedures in Method 1669 are designed to provide reliable results for the detection limits required in the proposed study. Water samples were collected from 1-m depth below the surface with an all-plastic pumping and filter system that minimized contamination or loss of metals from sampling equipment or airborne contamination. Field equipment blanks were used to evaluate contamination from sampling and storage of water samples.

The pumping system was acid-cleaned in the laboratory then sealed in clean polyethylene bags following Method 1669. In the field, the intake end of the sampling tube was held underwater at a depth of 1 m with an acid-cleaned Teflon weight. Before water samples were taken, the tubing and filter were flushed with five volumes of site water. The dissolved sample was collected, then the filter unit removed, and the total recoverable sample collected. Samples were taken for water quality parameters, including pH, salinity, and total suspended solids (TSS). Temperature was determined on site using an electronic thermometer that was hung in the surface water (15-cm depth). The electronic thermometer was compared with a National Institute of Standards and Technology certified mercury thermometer, which agreed within 0.1°C.

Water samples for metals were collected in Teflon bottles that were acid-cleaned and double-bagged, following Method 1669. After the water samples were collected, they were transported at 4°C to the Marine Science Lab (MSL), where the samples were acidified to pH 2 with high purity nitric acid in a class 100 clean room. One trip blank (for each of the three regions) of metal-free reagent water acidified to pH 2 was taken to the field and returned with the field samples without being opened in the field. One equipment blank was processed at each of the three regions by pumping unacidified reagent water through the field pumping system with and without a filter. This produced a total recoverable and a dissolved field equipment blank. A field duplicate sample for both total recoverable and dissolved metals, as well as water for matrix spikes, was collected at one station at each region.

Analytical Procedures

The analytical procedures were selected to provide detection limits generally a factor of five below the WDOE required detection limits (Table 4). Consideration was also given to the cost of various methods and the expected ambient concentrations of metals in Puget Sound. For the detection limits proposed in Table 4, the ambient concentrations for eight metals (arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc) in Puget Sound are usually above the proposed detection limits. The other five metals (antimony, beryllium, selenium, silver, and thallium) are typically present in Puget Sound and other coastal seawater at concentrations of 0.001 to 0.04 μg/L. The cost of detecting these metals in seawater at or below ambient concentrations would be very high, and therefore, we have recommended a detection limit that is well below the WDOE requirement but that may not detect these metals in Puget Sound. The analytical methods that were used are listed in Table 4. These methods have been developed recently by the EPA. Battelle had a significant role in the validation of these methods.

The sampling, storage, and analysis of the conventional water quality parameters followed the analytical procedures in EPA (1983) for pH (Method 150.1) and TSS (Method 160.2). Salinity samples were analyzed by the University of Washington Marine Chemistry Laboratory, with results traceable to a certified salinity standard. A standard salinity sample (Lot P83 11/10 1978) from the Institute of Oceanographic Sciences, Surrey, England, was analyzed three times during the analysis of the field samples. The standard is certified to contain a salinity of 35.003‰. The results from the university laboratory were in excellent agreement ranging from 34.984 to 35.005‰. The surface water temperature was measured in the field using a thermometer that was calibrated against a thermometer certified by the National Institute of Standards and Technology.

Table 4. Required and obtained detection limits and analytical methods for metals in marine water.

POLLUTANT PARAMETER	DETECTION LIMIT REQUIRED(1) (mg/L)	DETECTION LIMIT OBTAINED(2) (mg/L)	ANALYTICAL METHOD
Antimony (An)	3	0.009	EPA 1640
Arsenic (As)	1.0	0.14	EPA 1640
Beryllium (Be)	1.0	0.0003	EPA 1640
Cadmium (Cd)	0.1	0.006	EPA 1640
Chromium (Cr)	1.0	0.06	EPA 1640
Copper (Cu)	1.0	0.1	EPA 1640
Lead (Pb)	1.0	0.006	EPA 1640
Mercury (Hg)	0.2	0.0002	EPA 1631
Nickel (Ni)	1.0	0.08	EPA 1640
Selenium (Se)	2.0	0.02	EPA 1640
Silver (Ag)	0.2	0.01	EPA 1637
Thallium (Tl)	1.0	0.0006	EPA 1640
Zinc (Zn)	4.0	0.34	EPA 1640

(1) Detection limits required by WDOE.
(2) Detection limits obtained by Battelle based on 3.14 times the standard deviation for the mean of seven water samples from Cherry Point.

Quality Control Procedures

Quality control (QC) procedures provide the means of controlling and reporting the precision and bias (accuracy) of the results. The EPA methods that were followed for sampling and chemical analysis include established procedures that minimize errors. The QC results were used to assess the precision and accuracy of the data.

Three sets of field duplicates were collected, one at each region. The results from the duplicates are used to estimate precision. Three sets of matrix spikes were analyzed and the results used to estimate accuracy. Also, estimates of precision and accuracy were calculated from the analysis of triplicates of certified reference coastal seawater CASS-3 obtained from the National Research Council of Canada. Three trip blanks are used to evaluate contamination from bottles, acid, transportation, and storage. Three field equipment blanks are used to evaluate contamination from field sampling. Reagent or procedural blanks are used to evaluate contamination from the laboratory procedures including reagents, and plastic ware.

Results

Quality Control For Sample Contamination

The sources of contamination for metals were evaluated by analyzing field equipment blanks, trip blanks, and reagent blanks. Generally, contamination was very low compared to the concentration of metals in the field samples. Silver was the only metal that was usually not detected because of the reagent blank. For some dissolved samples, the reagent blank prevented the detection of chromium, zinc, and lead.

Two equipment blanks, one dissolved and one total, were processed from each of the three field sampling regions. For most of the metals there is no difference between the dissolved (filtered) and total (unfiltered) blanks, indicating that the filtering process did not cause significant contamination. For several metals (cadmium, chromium, copper, lead, and zinc) the dissolved blanks were slightly higher than the total blank for two of the three regions. The mean of the six equipment blanks was subtracted from all the field samples to blank-correct the field data for contamination that may have occurred during sampling, transport, storage, and analysis.

Three trip blanks were analyzed to evaluate contamination from transport and storage of the water samples. The trip blanks were reagent water that was acidified in the laboratory before the field sampling trips. The trip blanks were transported to the field, but never opened, then stored and analyzed with the field samples. The results of the trip blanks are very similar to those of the equipment blanks, which indicates the sampling process did not cause significant contamination.

Three reagent blanks were analyzed along with the field samples to estimate contamination caused by the analytical procedure. The mean of the three reagent blanks is similar to the equipment blanks and trip blanks, indicating that the reagent blanks are the most significant source of contamination. The means of the reagent blanks were subtracted from the results for the certified reference seawater (CASS-3) results.

Method Detection Limits

The method detection limits were determined for this study using the results for dissolved metals for seven stations (Cherry Point, CP-3 to CP-9). These Cherry Point results were relatively uniform, indicating that the water in that area was well mixed. The standard deviation of the mean for the seven stations was multiplied by 3.14 (Students t-value for 99% confidence level). The detection limits listed in Table 5 are equal to or well below those required by the WDOE-approved work plan. For silver and zinc, the mean blank is greater than the detection limit. Reduction of the blank for these two metals is needed to improve the analytical method. Several different lots of reagents were tested, but the reagent blank was not significantly improved.

Accuracy and Precision of Results for Metals

The accuracy of the results for metals is evaluated with both a certified reference material and matrix spikes. The reference materials used include CASS-3, a coastal seawater that is certified for seven metals, and 1641c certified for Hg. The results for the reference materials are shown in Table 6. The results were corrected for reagent blanks to remove that bias from our results. Our results were usually within the QC plan acceptance range of ±20% of the certified value for mercury, nickel, copper, cadmium, and lead. Several metals were outside the acceptance range either due to contamination or low recovery. Some of the chromium, lead, and zinc results were high, probably due to variability of our reagent blank for those three metals. Our reagent blank is relatively high and variable compared with the very low concentration in the reference material. Our results for arsenic averaged 20% lower than the certified value. Our results for selenium are near the reference value or below our detection limit. CASS-3 is not certified for selenium but a reference value is provided. The reference material is not certified for silver, beryllium, mercury, antimony, and thallium.

Matrix spikes and matrix spike duplicates were conducted on both a dissolved and total sample from each of the three field regions. The goal for matrix spike recovery was 80% to 120% and the goal for the relative percent difference (RPD) between duplicate spikes was 20%.

The matrix spikes recoveries for As, Cd, Cr, Cu, Hg, Ni, Pb, and Tl were usually in the range of 80% to 98%. Of the eight metals, the As recovery was often near 80%, which is consistent with the similar low recovery for As in CASS-3. The recoveries of Se and Sb are often in the 60% to 80% range. These two elements are present as anions in seawater, like As. The recovery of Ag was sometimes very low. However, the Ag recovery had no affect on the field results, which were below the detection limit and below the reagent blank. The matrix spike recoveries for Be were often near 80% and for Zn were near 50%. The low and inconsistent Zn recoveries may be due to the low concentration spiking. The results for Zn in CASS-3 were not low, which brings the significance of the Zn matrix spike recoveries into question.

The precision as determined from field duplicates and matrix spike duplicates is very good. Most of the duplicates agree within 10% RPD. The RPDs tend to increase when the concentrations of metals approach the detection limit, such as for silver, beryllium and selenium. The RPDs for the matrix spikes are lower, because the concentrations of metals are generally well above the detection limits.

Table 5. Method Detection Limit (MDL) determination

MDL Verification: MSL Code	Station ID	Type	Ag GFAA	Hg CVAA	Be 9 ICP-MS	Cr 52 ICP-MS	Ni 60 ICP-MS	Cu 63 ICP-MS	Zn 66 ICP-MS
			(concentration in µg/L, not blank corrected)						
1114WSPA*189	CP4	DISS	0.016	0.000390	0.00000	0.130	0.405	0.608	1.57
1114WSPA*190	CP5	DISS	0.011	0.000360	0.00000	0.147	0.377	0.628	1.39
1114WSPA*191	CP6	DISS	0.013	0.000239	0.00029	0.122	0.403	0.637	1.60
1114WSPA*192	CP7	DISS	0.008	0.000270	0.00000	0.124	0.408	0.606	1.34
1114WSPA*193	CP8	DISS	0.008	0.000235	0.00000	0.156	0.363	0.525	1.37
1114WSPA*194	CP9	DISS	0.008	0.000288	0.00000	0.156	0.365	0.564	1.56
1114WSPA*195	CP10	DISS	0.008	0.000374	0.00000	0.176	0.432	0.607	1.43
		Standard Deviation:	0.00320	0.0000654	0.000109	0.0200	0.0256	0.0390	0.107
		Mean:	0.0103	0.000308	0.0000410	0.144	0.393	0.597	1.46
		MDL (StDev x 3.14):	0.010	0.000205	0.000341	0.0627	0.0803	0.122	0.336

MSL Code	Station ID	Type	As 75 ICP-MS	Se 77 ICP-MS	Cd 112 ICP-MS	Sb 121 ICP-MS	Tl 205 ICP-MS	Pb 207 ICP-MS
			Continued-(concentration in µg/L, not blank corrected)					
1114WSPA*189	CP4	DISS	0.448	0.0088	0.0463	0.0673	0.00821	0.0124
1114WSPA*190	CP5	DISS	0.424	0.0197	0.0488	0.0638	0.00840	0.00811
1114WSPA*191	CP6	DISS	0.418	0.0000	0.0443	0.0639	0.00824	0.00727
1114WSPA*192	CP7	DISS	0.441	0.0068	0.0431	0.0630	0.00801	0.00759
1114WSPA*193	CP8	DISS	0.543	0.0197	0.0471	0.0615	0.00846	0.00656
1114WSPA*194	CP9	DISS	0.419	0.0081	0.0467	0.0605	0.00797	0.00725
1114WSPA*195	CP10	DISS	0.472	0.0155	0.0468	0.0584	0.00811	0.00784
		Standard Deviation:	0.0446	0.00733	0.00189	0.00284	0.000187	0.00195
		Mean:	0.452	0.0112	0.0461	0.0626	0.00820	0.00815
		MDL (StDev x 3.14):	0.140	0.0230	0.00594	0.00891	0.000588	0.00612

Table 6. Results for analysis of certified reference waters.

			W.S.P.A. Quality control results (concentration in µg/L, blank corrected)						
			Ag	Hg	Be 9	Cr 52	Ni 60	Cu 63	Zn 66
MSL Code	Station ID	Type	GFAA	CVAA	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
Standard Reference Material									
1641c			NA	1510	NA	NA	NA	NA	NA
1641c			NA	1480	NA	NA	NA	NA	NA
1641c			NA	1440	NA	NA	NA	NA	NA
	certified value			1470					
	range			±40					
	percent difference		NA	3%	NA	NA	NA	NA	NA
			NA	1%	NA	NA	NA	NA	NA
			NA	2%	NA	NA	NA	NA	NA
cass3 r1			0.010	NA	0.000341 U	0.180	0.388	0.573	2.88
cass3 r2			0.014	NA	0.000341 U	0.0994	0.360	0.518	1.27
cass3 r3			0.008	NA	0.000341 U	0.0903	0.347	0.513	1.68
cass3 rerun				NA	0.000341 U	0.220	0.367	0.559	1.88
	certified value		NC	NC	NC	0.092	0.386	0.517	1.24
	range					±0.006	±0.062	±0.062	±0.25
	percent difference		NA	NA	NA	95%	1%	11%	132%
			NA	NA	NA	8%	7%	0%	2%
			NA	NA	NA	2%	10%	1%	36%
			NA	NA	NA	139%	5%	8%	52%
Mean reagent blank (used to correct CASS)			0.010	0.000063	0.00055	0.0423	0.0131	0.0283	0.463

Table 6 (Continued). Results for analysis of certified reference waters.

			W.S.P.A. Quality control results continued (concentration in µg/L, blank corrected)					
MSL Code	Station ID	Type	As 75 ICP-MS	Se 77 ICP-MS	Cd 112 ICP-MS	Sb 121 ICP-MS	Tl 205 ICP-MS	Pb 207 ICP-MS
Standard Reference Material								
1641c			NA	NA	NA	NA	NA	NA
1641c			NA	NA	NA	NA	NA	NA
1641c			NA	NA	NA	NA	NA	NA
	certified value							
	range							
	percent difference		NA	NA	NA	NA	NA	NA
			NA	NA	NA	NA	NA	NA
			NA	NA	NA	NA	NA	NA
						NA	NA	NA
cass3 r1			0.926	0.0370	0.0343	0.107	0.0103	0.0160
cass3 r2			0.806	0.0230U	0.0330	0.119	0.0107	0.00999
cass3 r3			0.813	0.0230U	0.0331	0.119	0.0114	0.0103
cass3 rerun			0.929	0.0675	0.0321	0.123	0.0113	0.0145
	certified value		1.09	0.042R	0.030	NC	NC	0.0120
	range		±0.07		±0.005			±0.004
	percent difference		15%	12%	14%	NA	NA	34%
			26%	NA	10%	NA	NA	17%
			25%	NA	10%	NA	NA	14%
			15%	61%	7%	NA	NA	21%
Mean reagent blank (used to correct CASS)			0.0027	0.00289	0.00548	0.0111	0.00013	0.00425

Conventional Water Properties

The temperature, pH, salinity, and total suspended solids (TSS), referred to in this study as conventional water properties, were determined at the same stations where water was sampled for metals (Tables 1–3). The concentrations of these parameters were relatively uniform within each region, indicating the water was well mixed. The differences between the three regions were relatively small; the major exception was the lower salinity at Cherry Point due to the influence from the Fraser River. The temperature, pH, and salinity are similar to those reported by the WDOE (1997) Washington State Marine Water Quality Program for July 1994 and 1995 data collected at stations nearest the three regions sampled in this study.

The TSS concentrations generally ranged from 1 to 2 µg/L, which is typical for Puget Sound surface water during the summer. The concentration of phytoplankton appeared to be patchy within each region based both on the color of the water and the color of the filters used to determine the TSS. The TSS concentrations in Commencement Bay were significantly higher than those at the other two regions because of the turbidity from the Puyallup River, which was at high flow due to the late snow melt. The highest TSS was at station CB-9 located near the mouth of the river. Even though all stations in Commencement Bay were colored by the river plume, the salinity and temperature were fairly uniform, indicating relatively little dilution of the seawater.

Concentrations of Metals

The concentrations of total recoverable and dissolved metals in 10 water samples from each of the 3 regions are shown in Tables 7–9. These results have been blank-corrected using the mean of six field equipment blanks. Concentrations below the detection limit are flagged with a "U," and the detection limit is listed. The concentrations of silver, beryllium, and selenium were frequently below detection. The concentrations of dissolved chromium, mercury, lead, and zinc were occasionally below detection.

Table 7. Concentrations of total recoverable and dissolved metals in seawater.

MARCH POINT STATIONS
METALS IN WATER
Sample Date: June 30, 1997

(concentration in µg/L - blank corrected)

MSL Code	Station No.	Type	Ag GFAA	Hg CVAA	Be 9 ICP-MS	Cr 52 ICP-MS	Ni 60 ICP-MS	Cu 63 ICP-MS	Zn 66 ICP-MS
1114WSPA*39	MP1	TOTAL	0.011	0.000550	0.00284	0.225	0.453	0.434	0.886
1114WSPA*40	MP1 DUP	TOTAL	0.014	0.000576	0.00338	0.261	0.518	0.512	0.829
1114WSPA*44	MP2	TOTAL	0.010 U	0.000470	0.000733	0.287	0.499	0.465	0.487
1114WSPA*45	MP3	TOTAL	0.010 U	0.000411	0.00381	0.280	0.450	0.398	0.443
1114WSPA*46	MP4	TOTAL	0.010 U	0.000545	0.00101	0.308	0.490	0.432	0.502
1114WSPA*47	MP5	TOTAL	0.010 U	0.000654	0.00278	0.289	0.490	0.429	0.612
1114WSPA*48	MP6	TOTAL	0.010 U	0.000561	0.00304	0.289	0.519	0.488	0.550
1114WSPA*49	MP7	TOTAL	0.010 U	0.000538	0.00226	0.250	0.470	0.441	0.538
1114WSPA*50	MP8	TOTAL	0.010 U	0.000550	0.00249	0.407	0.497	0.459	0.708
1114WSPA*51	MP9	TOTAL	0.010 U	0.000631	0.00119	0.321	0.479	0.466	0.509
1114WSPA*52	MP10	TOTAL	0.010 U	0.000676	0.000484	0.279	0.522	0.489	1.26
1114WSPA*53	MP1	DISS	0.010 U	0.000320	0.000341 U	0.179	0.390	1.00	1.27
1114WSPA*54	MP1 DUP	DISS	0.010 U	0.000211	0.000341 U	0.165	0.426	0.405	0.176
1114WSPA*58	MP2	DISS	0.010 U	0.000257	0.000341 U	0.145	0.405	0.375	3.04
1114WSPA*59	MP3	DISS	0.010 U	0.000205 U	0.00265	0.183	0.398	0.403	0.323 J
1114WSPA*60	MP4	DISS	0.010 U	0.000546	0.00161	0.165	0.351	0.341	0.535
1114WSPA*61	MP5	DISS	0.010 U	0.000240	0.00173	0.181	0.403	0.357	0.297 J
1114WSPA*62	MP6	DISS	0.010 U	0.000572	0.000833	0.169	0.417	0.393	0.196 J
1114WSPA*63	MP7	DISS	0.010 U	0.000579	0.000341 U	0.162	0.381	0.375	0.261 J
1114WSPA*64	MP8	DISS	0.010 U	0.000321	0.00291	0.182	0.399	0.352	0.252 J
1114WSPA*65	MP9	DISS	0.010 U	0.000241	0.000883	0.161	0.440	0.398	0.176 J
1114WSPA*66	MP10	DISS	0.010 U	0.000205 U	0.000341 U	0.171	0.410	0.382	0.277 J
BLANKS									
1114WSPA*43 EB	MP1	TOTAL	0.029	0.000081	0.00381	0.121	0.0525	0.063	0.737
1114WSPA*57 EB	MP1	DISS	0.020	0.000069	0.000000	0.0885	0.0862	0.085	0.633
1114WSPA*197 TRP BLK			0.017	0.000210	0.00261	0.0977	0.0209	0.0638	0.631
Reagent Blank			0.007	0.000066	0.00164	0.0880	0.0241	0.0475	0.703
Mean Blank (used for blank correction):			0.018	0.000079	0.00063	0.0624	0.0401	0.0465	0.664
DETECTION LIMIT			**0.010**	**0.0002**	**0.0003**	**0.063**	**0.080**	**0.12**	**0.34**

Table 7. (Continued)

MARCH POINT STATIONS

METALS IN WATER

Sample Date: June 30, 1997

(concentration in µg/L - blank corrected)

MSL Code	Station No.	Type	As 75 ICP-MS	Se 77 ICP-MS	Cd 112 ICP-MS	Sb 121 ICP-MS	Tl 205 ICP-MS	Pb 207 ICP-MS
1114WSPA*39	MP1	TOTAL	0.743	0.0271	0.0591	0.0549	0.00911	0.0230
1114WSPA*40	MP1 DUP	TOTAL	0.964	0.0374	0.0664	0.0565	0.00896	0.0260
1114WSPA*44	MP2	TOTAL	1.01	0.0285	0.0611	0.0571	0.00903	0.0278
1114WSPA*45	MP3	TOTAL	1.15	0.0551	0.0672	0.0497	0.00901	0.0286
1114WSPA*46	MP4	TOTAL	1.09	0.0549	0.0662	0.0480	0.00928	0.0316
1114WSPA*47	MP5	TOTAL	1.10	0.0603	0.0666	0.0505	0.00907	0.0341
1114WSPA*48	MP6	TOTAL	0.987	0.0479	0.0611	0.0571	0.00868	0.0314
1114WSPA*49	MP7	TOTAL	1.05	0.0538	0.0652	0.0521	0.00849	0.0315
1114WSPA*50	MP8	TOTAL	1.04	0.0713	0.0658	0.0489	0.00891	0.0395
1114WSPA*51	MP9	TOTAL	0.982	0.0467	0.0543	0.0595	0.00854	0.0443
1114WSPA*52	MP10	TOTAL	1.01	0.0344	0.0594	0.0522	0.00941	0.0317
1114WSPA*53	MP1	DISS	0.963	0.0454	0.0555	0.0471	0.00805	0.0755
1114WSPA*54	MP1 DUP	DISS	0.962	0.0611	0.0573	0.0525	0.00810	0.00612 U
1114WSPA*58	MP2	DISS	1.04	0.0202 J	0.0612	0.0563	0.00919	0.00612 U
1114WSPA*59	MP3	DISS	1.18	0.110	0.0686	0.0505	0.00949	0.00612 U
1114WSPA*60	MP4	DISS	1.09	0.0533	0.0633	0.0560	0.00851	0.00612 U
1114WSPA*61	MP5	DISS	1.12	0.0563	0.0651	0.0584	0.00928	0.0118
1114WSPA*62	MP6	DISS	1.03	0.0645	0.0605	0.0521	0.00858	0.00612 U
1114WSPA*63	MP7	DISS	1.09	0.0653	0.0643	0.0537	0.00842	0.00612 U
1114WSPA*64	MP8	DISS	1.11	0.0358	0.0685	0.0525	0.00912	0.00612 U
1114WSPA*65	MP9	DISS	0.982	0.0476	0.0553	0.0552	0.00808	0.00612 U
1114WSPA*66	MP10	DISS	1.01	0.0506	0.0579	0.0494	0.00824	0.00612 U
BLANKS								
1114WSPA*43 EB	MP1	TOTAL	0.009	0.0151	0.00953	0.0268	0.000792	0.00632
1114WSPA*57 EB	MP1	DISS	0.003	0.0174	0.00989	0.0209	0.000943	0.00748
1114WSPA*197 TRP BLK			0.0018	0.0000	0.00849	0.0141	0.0000	0.00677
Reagent Blank			0.0064	0.0087	0.00756	0.0134	0.00024	0.00737
Mean Blank (used for blank correction):			0.00232	0.00541	0.00731	0.0151	0.000651	0.00641
DETECTION LIMIT			**0.14**	**0.023**	**0.006**	**0.009**	**0.0006**	**0.006**

Table 8. Concentrations of total recoverable and dissolved metals in seawater.

CHERRY POINT STATIONS
METALS IN WATER
Sample Date: July 16, 1997

			(concentration in µg/L - blank corrected)						
			Ag	Hg	Be 9	Cr 52	Ni 60	Cu 63	Zn 66
MSL Code	Station ID	Type	GFAA	CVAA	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
1114WSPA*168	CP1	TOTAL	0.010 U	0.000465	0.000769	0.212	0.436	0.672	1.40
1114WSPA*169	CP1 Dup	TOTAL	0.010 U	0.000512	0.000341 U	0.217	0.459	0.701	1.69
1114WSPA*173	CP2	TOTAL	0.010 U	0.000430	0.000341 U	0.168	0.385	0.583	1.07
1114WSPA*174	CP3	TOTAL	0.010 U	0.000455	0.000341 U	0.111	0.400	0.636	1.13
1114WSPA*175	CP4	TOTAL	0.010 U	0.000458	0.000341 U	0.104	0.414	0.628	1.09
1114WSPA*176	CP5	TOTAL	0.010 U	0.000566	0.000341 U	0.115	0.439	0.657	0.948
1114WSPA*177	CP6	TOTAL	0.010 U	0.000561	0.000341 U	0.130	0.440	0.674	1.15
1114WSPA*178	CP7	TOTAL	0.010 U	0.000382	0.000341 U	0.146	0.402	0.625	0.983
1114WSPA*179	CP8	TOTAL	0.010 U	0.000497	0.000341 U	0.135	0.340	0.510	0.821
1114WSPA*180	CP9	TOTAL	0.010 U	0.000449	0.000341 U	0.153	0.384	0.591	1.20
1114WSPA*181	CP10	TOTAL	0.010 U	0.000563	0.000341 U	0.0879	0.411	0.601	0.990
1114WSPA*182	CP1	DISS	0.010 U	0.000395	0.000341 U	0.0627 U	0.341	0.498	0.637
1114WSPA*183	CP1 Dup	DISS	0.010 U	0.000283	0.000341 U	0.0933	0.374	0.530	0.793
1114WSPA*187	CP2	DISS	0.014	0.000235	0.000341 U	0.0646	0.364	0.560	1.08
1114WSPA*188	CP3	DISS	0.010 U	0.000301	0.000341 U	0.134	0.361	0.553	0.567
1114WSPA*189	CP4	DISS	0.010 U	0.000390	0.000341 U	0.0680	0.365	0.562	0.906
1114WSPA*190	CP5	DISS	0.010 U	0.000360	0.000341 U	0.0841	0.337	0.582	0.730
1114WSPA*191	CP6	DISS	0.010 U	0.000239	0.000341 U	0.0627 U	0.363	0.591	0.932
1114WSPA*192	CP7	DISS	0.010 U	0.000270	0.000341 U	0.0627 U	0.368	0.560	0.672
1114WSPA*193	CP8	DISS	0.010 U	0.000235	0.000341 U	0.0938	0.323	0.479	0.708
1114WSPA*194	CP9	DISS	0.010 U	0.000288	0.000341 U	0.0938	0.324	0.518	0.895
1114WSPA*195	CP10	DISS	0.010 U	0.000374	0.000341 U	0.113	0.392	0.560	0.763
BLANKS									
1114WSPA*172	CP1	TOTAL	0.011	0.000100	0.000000	0.000	0.0000	0.000	0.10
1114WSPA*186	CP1	DISS	0.021	0.000028	0.000000	0.0390	0.0507	0.049	1.36
1114WSPA*197 TRP BLK			0.011	0.000054	0.000000	0.0752	0.0181	0.0346	1.07
Reagent Blank			0.008	0.000037	0.00000	0.0000	0.0000	0.0000	0.0355
Mean Blank (used for blank correction):			0.018	0.000079	0.00063	0.0624	0.0401	0.0465	0.664
DETECTION LIMIT			**0.010**	**0.000205**	**0.00034085**	**0.0627**	**0.0803**	**0.122**	**0.336**

Table 8. (Continued)

CHERRY POINT STATIONS

METALS IN WATER

Sample Date: July 16, 1997

MSL Code	Station ID	Type	(concentration in µg/L - blank corrected) **As 75** ICP-MS	**Se 77** ICP-MS	**Cd 112** ICP-MS	**Sb 121** ICP-MS	**Tl 205** ICP-MS	**Pb 207** ICP-MS
1114WSPA*168	CP1	TOTAL	0.590	0.0485	0.0446	0.0461	0.00735	0.0154
1114WSPA*169	CP1 Dup	TOTAL	0.539	0.0717	0.0481	0.0436	0.00758	0.0176
1114WSPA*173	CP2	TOTAL	0.432	0.0230 U	0.0439	0.0440	0.00770	0.0141
1114WSPA*174	CP3	TOTAL	0.411	0.0238	0.0447	0.0432	0.00730	0.0129
1114WSPA*175	CP4	TOTAL	0.450	0.0230 U	0.0480	0.0442	0.00739	0.0164
1114WSPA*176	CP5	TOTAL	0.489	0.0272	0.0480	0.0443	0.00733	0.0161
1114WSPA*177	CP6	TOTAL	0.433	0.0230 U	0.0441	0.0397	0.00683	0.0176
1114WSPA*178	CP7	TOTAL	0.447	0.0230 U	0.0461	0.0403	0.00698	0.0137
1114WSPA*179	CP8	TOTAL	0.465	0.0230 U	0.0403	0.0347	0.00653	0.0109
1114WSPA*180	CP9	TOTAL	0.459	0.0403	0.0473	0.0482	0.00749	0.0197
1114WSPA*181	CP10	TOTAL	0.505	0.0230 U	0.0487	0.0466	0.00733	0.0147
1114WSPA*182	CP1	DISS	0.493	0.0230 U	0.0330	0.0474	0.00724	0.00612 U
1114WSPA*183	CP1 Dup	DISS	0.466	0.0230 U	0.0318	0.0513	0.00738	0.00612 U
1114WSPA*187	CP2	DISS	0.414	0.0298	0.0312	0.0502	0.00745	0.00612 U
1114WSPA*188	CP3	DISS	0.577	0.0308	0.0368	0.0427	0.00744	0.0290
1114WSPA*189	CP4	DISS	0.445	0.0230 U	0.0390	0.0522	0.00755	0.00612 U
1114WSPA*190	CP5	DISS	0.421	0.0230 U	0.0414	0.0487	0.00775	0.00612 U
1114WSPA*191	CP6	DISS	0.416	0.0230 U	0.0370	0.0488	0.00758	0.00612 U
1114WSPA*192	CP7	DISS	0.439	0.0230 U	0.0357	0.0479	0.00736	0.00612 U
1114WSPA*193	CP8	DISS	0.541	0.0230 U	0.0398	0.0464	0.00781	0.00612 U
1114WSPA*194	CP9	DISS	0.416	0.0230 U	0.0394	0.0454	0.00732	0.00612 U
1114WSPA*195	CP10	DISS	0.470	0.0230 U	0.0395	0.0433	0.00746	0.00612 U
BLANKS								
1114WSPA*172	CP1	TOTAL	0.000	0.0000	0.00103	0.0014	0.00000	0.00008
1114WSPA*186	CP1	DISS	0.000	0.0000	0.0106	0.0141	0.000724	0.00722
1114WSPA*197 TRP BLK			0.0037	0.0000	0.00691	0.0121	0.000037	0.00455
Reagent Blank			0.0000	0.0000	0.00090	0.0013	0.00000	0.00000
	Mean Blank (used for blank correction):		0.00232	0.00541	0.00731	0.0151	0.000651	0.00641
DETECTION LIMIT			**0.140**	**0.0230**	**0.00594**	**0.00891**	**0.000588**	**0.00612**

Table 9. Concentrations of total recoverable and dissolved metals in seawater.

COMMENCEMENT BAY STATIONS
CONVENTIONAL WATER PROPERTIES
Sample Date July 11, 1997

(concentration in µg/L - blank corrected)

MSL Code	Station No.	Type	Ag GFAA	Hg CVAA	Be 9 ICP-MS	Cr 52 ICP-MS	Ni 60 ICP-MS	Cu 63 ICP-MS	Zn 66 ICP-MS
1114WSPA*104	CB1	TOTAL	0.010 U	0.000711	0.000957	0.232	0.480	1.02	2.35
1114WSPA*105	CB1 DUP	TOTAL	0.010 U	0.000634	0.00175	0.279	0.442	0.99	2.16
1114WSPA*109	CB2	TOTAL	0.010 U	0.000909	0.00212	0.202	0.436	1.28	3.74
1114WSPA*110	CB3	TOTAL	0.029	0.000755	0.00166	0.220	0.466	0.782	1.30
1114WSPA*111	CB4	TOTAL	0.010 U	0.000342	0.00270	0.164	0.386	0.627	0.896
1114WSPA*112	CB5	TOTAL	0.010 U	0.000941	0.000341 U	0.200	0.454	1.25	4.36
1114WSPA*113	CB6	TOTAL	0.010 U	0.000833	0.00300	0.250	0.464	1.08	1.88
1114WSPA*114	CB7	TOTAL	0.010 U	0.000326	0.00219	0.171	0.395	0.620	1.09
1114WSPA*115	CB8	TOTAL	0.010 U	0.000820	0.000341 U	0.148	0.409	0.693	0.994
1114WSPA*116	CB9	TOTAL	0.010 U	0.000862	0.00408	0.370	0.548	1.02	1.21
1114WSPA*117	CB10	TOTAL	0.010 U	0.000550	0.000473	0.163	0.388	0.730	1.00
1114WSPA*118	CB1	DISS	0.010 U	0.000284	0.000341 U	0.128	0.381	0.577	1.85
1114WSPA*119	CB1 DUP	DISS	0.010 U	0.000219	0.000592	0.129	0.351	0.584	1.57
1114WSPA*123	CB2	DISS	0.010 U	0.000286	0.000341 U	0.0828	0.373	0.916	2.99
1114WSPA*124	CB3	DISS	0.010 U	0.000205 U	0.00117	0.128	0.335	0.505	0.783
1114WSPA*125	CB4	DISS	0.010 U	0.000208	0.000341 U	0.0979	0.348	0.467	0.657
1114WSPA*126	CB5	DISS	0.010 U	0.000497	0.000341 U	0.0994	0.498	1.09	4.31
1114WSPA*127	CB6	DISS	0.010 U	0.000208	0.000341 U	0.0722	0.353	0.637	1.33
1114WSPA*128	CB7	DISS	0.010 U	0.000205 U	0.000341 U	0.0928	0.333	0.491	0.735
1114WSPA*129	CB8	DISS	0.010 U	0.000233	0.000341 U	0.0781	0.276	0.439	0.572
1114WSPA*130	CB9	DISS	0.010 U	0.000205 U	0.000341 U	0.160	0.343	0.437	0.528
1114WSPA*131	CB10	DISS	0.010 U	0.000422	0.000341 U	0.140	0.337	0.531	0.844
BLANKS									
1114WSPA*108 EB	CB1	TOTAL	0.011	0.00112	0.000341 U	0.0627 U	0.0803 U	0.122 U	0.475
1114WSPA*122 EB	CB1	DISS	0.014	0.000205 U	0.000341 U	0.0872	0.0803 U	0.122 U	0.680
1114WSPA*197 TRP BLK			0.011	0.000205 U	0.000341 U	0.0666	0.0803 U	0.122 U	0.624
Reagent Blank			0.014	0.000087	0.00000	0.0390	0.0151	0.0376	0.651
	Mean Blank (used for blank correction):		0.018	0.000079	0.00063	0.0624	0.0401	0.0465	0.664
DETECTION LIMIT			**0.010**	**0.0002**	**0.0003**	**0.063**	**0.080**	**0.12**	**0.34**

Table 9. (Continued)

COMMENCEMENT BAY STATIONS
CONVENTIONAL WATER PROPERTIES
Sample Date July 11, 1997

(concentration in μg/L - blank corrected)

MSL Code	Station No.	Type	As 75 ICP-MS	Se 77 ICP-MS	Cd 112 ICP-MS	Sb 121 ICP-MS	Tl 205 ICP-MS	Pb 207 ICP-MS
1114WSPA*104	CB1	TOTAL	1.03	0.0505	0.0574	0.0647	0.00902	0.0663
1114WSPA*105	CB1 DUP	TOTAL	1.03	0.0564	0.0607	0.0735	0.00837	0.0580
1114WSPA*109	CB2	TOTAL	1.00	0.0230 U	0.0572	0.0703	0.0103	0.141
1114WSPA*110	CB3	TOTAL	1.02	0.0404	0.0628	0.0785	0.00983	0.0657
1114WSPA*111	CB4	TOTAL	0.990	0.0303	0.0625	0.0803	0.00966	0.0453
1114WSPA*112	CB5	TOTAL	1.13	0.0294	0.0524	0.0769	0.00820	0.252
1114WSPA*113	CB6	TOTAL	1.00	0.0367	0.0591	0.0764	0.00889	0.143
1114WSPA*114	CB7	TOTAL	0.990	0.0398	0.0637	0.0745	0.00954	0.0479
1114WSPA*115	CB8	TOTAL	0.978	0.0256	0.0611	0.0808	0.00975	0.0563
1114WSPA*116	CB9	TOTAL	1.03	0.0643	0.0633	0.0706	0.0115	0.102
1114WSPA*117	CB10	TOTAL	0.985	0.0452	0.0629	0.0812	0.00919	0.0680
1114WSPA*118	CB1	DISS	0.971	0.0274	0.0582	0.0851	0.00893	0.00809
1114WSPA*119	CB1 DUP	DISS	0.943	0.0448	0.0575	0.0869	0.00897	0.00857
1114WSPA*123	CB2	DISS	0.925	0.0692	0.0538	0.0823	0.00946	0.0154
1114WSPA*124	CB3	DISS	0.902	0.0425	0.0588	0.0809	0.00923	0.00809
1114WSPA*125	CB4	DISS	0.931	0.0328	0.0609	0.0801	0.00977	0.00849
1114WSPA*126	CB5	DISS	0.991	0.0230 U	0.0531	0.0751	0.00819	0.0250
1114WSPA*127	CB6	DISS	0.909	0.0299	0.0548	0.0897	0.00823	0.0130
1114WSPA*128	CB7	DISS	0.920	0.0312	0.0597	0.0774	0.00953	0.00978
1114WSPA*129	CB8	DISS	0.797	0.105	0.0485	0.0632	0.00756	0.00969
1114WSPA*130	CB9	DISS	0.920	0.0435	0.0616	0.0726	0.00953	0.0151
1114WSPA*131	CB10	DISS	0.914	0.0230 U	0.0590	0.0738	0.00893	0.0120
BLANKS								
1114WSPA*108 EB	CB1	TOTAL	0.140 U	0.0230 U	0.00594 U	0.0125	0.000833	0.00612 U
1114WSPA*122 EB	CB1	DISS	0.140 U	0.0230 U	0.00843	0.0152	0.000618	0.0137
1114WSPA*197 TRP BLK			0.140 U	0.0230 U	0.00793	0.0144	0.000588 U	0.00612 U
Reagent Blank			0.0016	0.0000	0.00798	0.0187	0.00015	0.00537
Mean Blank (used for blank correction):			0.00232	0.00541	0.00731	0.0151	0.000651	0.00641
DETECTION LIMIT			**0.14**	**0.023**	**0.006**	**0.009**	**0.0006**	**0.006**

Discussion

Statistical Methods

Descriptive statistics were used to evaluate the distribution of blank-corrected concentration of each total and dissolved metal from water samples collected from the three Puget Sound regions. Analytical replicates for a given concentration were averaged prior to analysis. The distribution of each metal concentration within a region was characterized by the mean, median, minimum and maximum values, and the 25th and 75th quartiles. The range between the two quartiles provides a useful nonparametric interval bounding the distribution. The nonparametric median and first and third quartiles are not as greatly affected by single large observations, which can skew a mean and parametric confidence intervals. Possible outliers were defined as observations greater than three times the median value.

The mean concentrations of each total and dissolved metal from the three regions were compared using Tukey's Honestly Significant Difference (HSD) test. The HSD test compared all possible pairwise comparisons between regions using an experiment-wide error rate of $\alpha = 0.05$. Metal concentrations were transformed to the natural logarithm to minimize the heterogeneity of within-class variance. The Kruskal-Wallis nonparametric test of the equality of the three medians was used when the assumption of equal within-class variance was still not satisfied following the natural logarithmic transformation.

Particulate concentrations of each metal for each region were estimated by the difference in the median total and dissolved concentrations. The difference between median values was used rather than the difference between individual observations of the total and dissolved concentrations in an attempt to provide a more representative estimate of the particulate concentration in a region. If the median dissolved concentration was greater than the median total concentration, then the particulate concentration was not calculable.

Statistical Results

Three observations from Station MP1 at March Point were not used in the statistical analysis, because they were greater than two times the replicate result. These observations were for dissolved copper, zinc, and lead. The dissolved concentrations of these metals at this region were estimated only from the replicate with the lower concentration.

The distribution of the total concentration of each metal for each region is characterized in Table 10. The standard deviations for the majority of metals were generally less than 5%. Five observations had extreme values in relation to the median and could be considered outliers. Stations MP1 and CB3 had extreme values of total silver. Station MP8 had an extreme value of chromium, and Stations MP1 and CP1 had extreme values of zinc and selenium, respectively. Because there is no apparent reason for these high values, the data were not removed from further analysis.

The distribution of the concentration of dissolved metals is characterized in Table 11. The standard deviations for the majority of metals were again generally less than 5%. Ten observations had extreme values in relation to the median and could be considered outliers. Stations CP2 and CB2 had extreme values of total silver and beryllium, respectively. Station MP4 had an extreme low value of nickel, whereas Station CB5 had an extreme high value. Station MP2 had an extreme high value of zinc, and Station CB8 had an extreme low value of selenium. Stations CP3 and CB8 had extreme values of cadmium, and stations MP5 and CP3 had extreme values of lead. Again, because there is no apparent reason for these high and low values, the data were not removed from further analysis.

Concentrations of total and dissolved beryllium, chromium, nickel, arsenic, selenium, and cadmium were statistically greater ($\alpha = 0.05$) at March Point than Commencement Bay and Cherry Point (Table 12). Concentrations of copper, antimony, and thallium were statistically greater in Commencement Bay than at March Point and Cherry Point. Cherry Point tended to have the lowest concentrations of both the total and dissolved metals except for copper and zinc. Note that when stations are not listed in the

columns for statistical comparisons in Table 12, the missing values were not significantly different from those of either of the listed stations.

Variability Within Regions

Based on one sampling event, two regions, Cherry Point and March Point, apparently are not affected by local contamination. Commencement Bay is the only region that appears to have significant within-region differences for metals in water, with significantly higher concentrations of mercury, copper, zinc, and lead than the other regions, presumably due to industrial activity. The concentrations of these four metals are higher at stations CB2 and CB5 than at the other eight stations. The temperatures were the highest and the salinity the lowest at CB2 and CB5, indicating that these stations, located outside the Hylebos Waterway, are affected by the waterway. During the time of sampling, the tide was ebbing and the surface current was to the northwest, which is consistent with the assumption that the water chemistry at stations CB2 and CB5 is influenced by local sources in the northeastern area of the region.

Comparison to Previously Published Results on the Concentrations of Metals in Puget Sound

Over the past 20 years, there have been several studies in Puget Sound waters that used analytical methods sensitive enough to detect many of the metals discussed in the present study. The Pacific Marine Environmental Laboratory (PMEL) of NOAA published several articles on the distribution, sources, and transport of metals in Puget Sound, including Commencement Bay (NOAA 1987; Paulson and Feely 1985). The WDOE also has studied metals in Commencement Bay (Stinson and Norton 1987). The Municipality of Metropolitan Seattle (METRO) study on toxicant pretreatment measured 13 metals in the central Puget Sound and in the Strait of Juan de Fuca (Romberg et al. 1984). Other studies reported results for silver, arsenic, and mercury (Bloom and Crecelius 1983; Bloom and Crecelius 1984; Carpenter et al. 1978; and Crecelius et al. 1975). In general, the results of all these past studies are similar to the results in the present study. The metals that appear to be enriched in urban regions are chromium, copper, mercury, nickel, lead, and zinc. Several metals that were not significantly enriched by anthropogenic activities included arsenic, cadmium, antimony, and selenium. Several metals (silver, beryllium, and thallium) have not been studied adequately to determine geographical trends.

Table 10. Descriptive statistics of the total concentration (µg/L, blank corrected) of each metal for each region (n = 10).

Metal	Region	Mean	Median	St. Dev	Min	Max	Q1	Q3
Ag	March Point	0.0103	0.0100	0.00079	0.0100	0.0125	0.0100	0.0100U
	Cherry Point	0.0100	0.0100	0.00000	0.0100	0.0100	0.0100	0.0100U
	Commencement Bay	0.0119	0.0100	0.00601	0.0100	0.0290	0.0100	0.0100U
Hg	March Point	0.000560	0.000560	0.00008	0.000410	0.000680	0.000520	0.000640
	Cherry Point	0.000490	0.000470	0.00006	0.000380	0.000570	0.000440	0.000560
	Commencement Bay	0.000700	0.000790	0.00022	0.000330	0.000940	0.000500	0.000870
Be	March Point	0.00272	0.00300	0.00115	0.00111	0.00444	0.00157	0.00369
	Cherry Point	0.000530	0.000340	0.00029	0.000340	0.00118	0.000340	0.000710
	Commencement Bay	0.00244	0.00252	0.00126	0.000860	0.00471	0.00107	0.00341
Cr	March Point	0.291	0.284	0.04560	0.239	0.403	0.268	0.307
	Cherry Point	0.132	0.129	0.03660	0.0837	0.210	0.105	0.153
	Commencement Bay	0.210	0.197	0.06580	0.144	0.365	0.159	0.247

Table 10. (Continued)

Ni	March Point	0.530	0.530	0.02146	0.490	0.562	0.517	0.544
	Cherry Point	0.446	0.447	0.03230	0.381	0.488	0.425	0.480
	Commencement Bay	0.481	0.485	0.04950	0.427	0.588	0.433	0.505
Cu	March Point	0.500	0.508	0.02877	0.444	0.535	0.478	0.523
	Cherry Point	0.666	0.673	0.05140	0.556	0.733	0.635	0.708
	Commencement Bay	0.955	0.939	0.25000	0.666	1.33	0.723	1.17
Zn	March Point	0.4466	0.336	0.21830	0.336	1.01	0.336	0.498
	Cherry Point	0.8456	0.832	0.19420	0.574	1.30	0.727	0.917
	Commencement Bay	1.625	1.011	1.23300	0.649	4.11	0.752	2.38
As	March Point	1.03	1.03	0.08100	0.856	1.16	0.988	1.09
	Cherry Point	0.468	0.457	0.04440	0.413	0.567	0.435	0.496
	Commencement Bay	1.02	1.00	0.04340	0.980	1.13	0.991	1.03
Se	March Point	0.0539	0.0563	0.01350	0.0340	0.0768	0.0393	0.0618
	Cherry Point	0.0314	0.0244	0.01395	0.0230	0.0655	0.0230	0.0359
	Commencement Bay	0.0437	0.0437	0.01372	0.0230	0.0697	0.0338	0.0526
Cd	March Point	0.0703	0.0713	0.00410	0.0616	0.0746	0.0680	0.0736
	Cherry Point	0.0451	0.0455	0.00255	0.0396	0.0480	0.0434	0.0473
	Commencement Bay	0.0597	0.0611	0.00355	0.0518	0.0630	0.0579	0.0623
Sb	March Point	0.0682	0.0673	0.00398	0.0631	0.0746	0.0646	0.0722
	Cherry Point	0.0399	0.0410	0.00388	0.0316	0.0451	0.0371	0.0422
	Commencement Bay	0.0728	0.0736	0.00456	0.0660	0.0781	0.0675	0.0773
Tl	March Point	0.00960	0.00967	0.00030	0.00914	0.0101	0.00930	0.00977
	Cherry Point	0.00788	0.00798	0.00035	0.00718	0.00835	0.00759	0.00812
	Commencement Bay	0.0102	0.0103	0.00093	0.00885	0.0122	0.00949	0.0106
Pb	March Point	0.0389	0.0380	0.00573	0.0309	0.0507	0.0348	0.0419
	Cherry Point	0.0144	0.0146	0.00252	0.0101	0.0189	0.0127	0.0159
	Commencement Bay	0.0975	0.0660	0.06480	0.0444	0.251	0.0534	0.141

Table 11. Descriptive statistics for the dissolved concentration (μg/L, blank corrected) of each metal for each region (n = 10).

Metal	Region	Mean	Median	St. Dev.	Min	Max	Q1	Q3
Ag	March Point	0.0100	0.0100	0.00000	0.0100	0.0100	0.0100	0.0100
	Cherry Point	0.0104	0.0100	0.00126	0.0100	0.0140	0.0100	0.0100
	Commencement Bay	0.0100	0.0100	0.00000	0.0100	0.0100	0.0100	0.0100
Hg	March Point	0.000340	0.000260	0.00016	0.000210	0.000580	0.000230	0.000550
	Cherry Point	0.000300	0.000290	0.00006	0.000230	0.000390	0.000240	0.000360
	Commencement Bay	0.000270	0.000220	0.00010	0.000210	0.000500	0.000210	0.000320
Be	March Point	0.00166	0.00149	0.00117	0.000150	0.00354	0.000570	0.00259
	Cherry Point	0.000340	0.000340	0.00000	0.000340	0.000340	0.000340	0.000340
	Commencement Bay	0.000580	0.000340	0.00047	0.000340	0.00180	0.000340	0.000640
Cr	March Point	0.165	0.166	0.01165	0.141	0.179	0.157	0.177
	Cherry Point	0.0826	0.0779	0.02258	0.0627	0.129	0.0627	0.0945
	Commencement Bay	0.104	0.0945	0.02952	0.0680	0.156	0.0774	0.127
Ni	March Point	0.441	0.444	0.02332	0.391	0.480	0.434	0.452
	Cherry Point	0.396	0.402	0.02128	0.363	0.432	0.374	0.406
	Commencement Bay	0.396	0.386	0.05630	0.316	0.538	0.374	0.408
Cu	March Point	0.425	0.425	0.02246	0.387	0.451	0.402	0.446
	Cherry Point	0.594	0.606	0.03410	0.525	0.637	0.563	0.613
	Commencement Bay	0.656	0.564	0.22020	0.484	1.14	0.506	0.753
Zn	March Point	0.581	0.336	0.77600	0.336	2.79	0.336	0.336
	Cherry Point	0.552	0.500	0.15030	0.336	0.836	0.452	0.666
	Commencement Bay	1.21	0.567	1.25200	0.336	4.07	0.391	1.78
As	March Point	1.06	1.06	0.06820	0.965	1.18	1.00	1.11
	Cherry Point	0.464	0.444	0.05660	0.417	0.579	0.418	0.497
	Commencement Bay	0.919	0.922	0.04950	0.799	0.993	0.909	0.940
Se	March Point	0.0611	0.0587	0.02330	0.0256	0.116	0.0501	0.0701
	Cherry Point	0.0255	0.0230	0.00535	0.0230	0.0362	0.0230	0.0260
	Commencement Bay	0.0482	0.0399	0.02627	0.0230	0.111	0.0327	0.0553
Cd	March Point	0.0694	0.0696	0.00469	0.0626	0.0759	0.0648	0.0732
	Cherry Point	0.0365	0.0373	0.00332	0.0306	0.0408	0.0342	0.0389
	Commencement Bay	0.0561	0.0576	0.00416	0.0478	0.0609	0.0529	0.0593

Table 11. (Continued)

Metal	Region	Mean	Median	St. Dev.	Min	Max	Q1	Q3
Sb	March Point	0.0685	0.0682	0.00305	0.0645	0.0735	0.0654	0.0711
	Cherry Point	0.0444	0.0452	0.00302	0.0396	0.0491	0.0418	0.0465
	Commencement Bay	0.0750	0.0757	0.00750	0.0601	0.0866	0.0704	0.0801
Tl	March Point	0.00935	0.00919	0.00053	0.00872	0.0101	0.00885	0.00986
	Cherry Point	0.00815	0.00810	0.00017	0.00796	0.00846	0.00800	0.00828
	Commencement Bay	0.00959	0.00974	0.00072	0.00821	0.0104	0.00887	0.0102
Pb	March Point	0.00955	0.00877	0.00325	0.00607	0.0182	0.00810	0.00977
	Cherry Point	0.00832	0.00612	0.00696	0.00612	0.0281	0.00612	0.00612
	Commencement Bay	0.0117	0.0101	0.00515	0.00727	0.0242	0.00763	0.0143

Table 12. Statistical comparisons and ranking of regions for the total and dissolved concentrations and estimated particulate concentrations of each metal (µg/L, blank corrected). Significantly greater concentrations are designated by a "greater than" sign (>), and concentrations not significantly different are separated by a comma.

Metal	Region	Total		Dissolved		Estimated Particulate Concentration
		Median	Statistical Comparison	Median	Statistical Comparison	
Ag	March Point	0.0100	NS	0.0100	NS	0.0000
	Cherry Point	0.0100		0.0100		0.0000
	Commencement Bay	0.0100		0.0100		0.0000
Hg	March Point	0.000560	CB>CP	0.000260	NS	0.000300
	Cherry Point	0.000470		0.000290		0.000180
	Commencement Bay	0.000790		0.000220		0.000570
Be	March Point	0.00300	MP,CB>CP	0.00149	MP>CB,CP	0.00151
	Cherry Point	0.000340		0.000340		0.00000
	Commencement Bay	0.00252		0.000340		0.00218
Cr	March Point	0.284	MP>CB>CP	0.166	MP>CB,CP	0.118
	Cherry Point	0.129		0.0779		0.0506
	Commencement Bay	0.197		0.0945		0.102
Ni	March Point	0.530	MP>CB,CP	0.444	MP>CB,CP	0.0863
	Cherry Point	0.447		0.402		0.0448
	Commencement Bay	0.485		0.386		0.0995
Cu	March Point	0.508	CB>CP>MP	0.425	CB,CP>MP	0.0835
	Cherry Point	0.673		0.606		0.0665
	Commencement Bay	0.939		0.564		0.375
Zn	March Point	0.336	CB,CP>MP	0.336	NS	0.000
	Cherry Point	0.832		0.500		0.333
	Commencement Bay	1.011		0.567		0.444

Table 12. (Continued)

Metal	Region	Total		Dissolved		Estimated Particulate Concentration
		Median	Statistical Comparison	Median	Statistical Comparison	
As	March Point	1.03	MP,CB>CP	1.06	MP>CB>CP	NA
	Cherry Point	0.457		0.444		0.0124
	Commencement Bay	1.00		0.922		0.0801
Se	March Point	0.0563	MP>CP	0.0587	MP,CB>CP	NA
	Cherry Point	0.0244		0.0230		0.00144
	Commencement Bay	0.0437		0.0399		0.00379
Cd	March Point	0.0713	MP>CB>CP	0.0696	MP>CB>CP	0.00175
	Cherry Point	0.0455		0.0373		0.00823
	Commencement Bay	0.0611		0.0576		0.00350
Sb	March Point	0.0673	CB,MP>CP	0.0682	CB>MP>CP	NA
	Cherry Point	0.0410		0.0452		NA
	Commencement Bay	0.0736		0.0757		NA
Tl	March Point	0.00967	CB,MP>CP	0.00919	CB,MP>CP	0.000480
	Cherry Point	0.00798		0.00810		NA
	Commencement Bay	0.0103		0.00974		0.000510
Pb	March Point	0.0380	CB>MP>CP	0.00877	NS	0.0292
	Cherry Point	0.0146		0.00612		0.00848
	Commencement Bay	0.0660		0.0101		0.0560

MP = March Point
CP = Cherry Point
CB = Commencement Bay
NS = Not Significant
NA = Not Applicable

Conclusions

The concentrations of 13 metals were determined in three regions of Puget Sound during the summer of 1997. The seawater samples were collected and analyzed using EPA methods designed to minimize sample contamination and to determine the ambient concentrations of metals in uncontaminated coastal seawater. Results for field equipment blanks and reagent blanks indicate that very little contamination occurred from sampling and analysis. The detection limits obtained were well below those required by the WDOE. Several metals including silver, beryllium, lead, selenium, and zinc were near or below the detection limits in some samples. Both dissolved metals (filtered at 0.45 µm) and total recoverable metals were determined at 10 stations in surface water (1-m depth). Samples were collected near Cherry Point (northwest of Bellingham), March Point (near Anacortes), and Commencement Bay.

The concentrations of metals were very uniform within a region, except for Commencement Bay, where several stations indicate local industrial contamination of copper, mercury, lead, and zinc. These

results are consistent with results from other studies that were able to quantify metals at similar detection limits. There were relatively small differences between the mean concentrations of metals in the three regions. Cherry Point samples contained lower concentrations of arsenic, cadmium, antimony, selenium, and thallium, probably due to dilution of seawater by the Fraser River.

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Toxicity of Sediments in Northern Puget Sound: A National Perspective

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Introduction

Toxic substances introduced into aquatic ecosystems can bind to particles and collect in deposited sediments, therefore representing a potential toxicological threat the resident biota if concentrations become sufficiently elevated. Toxic chemicals are found in a wide range of concentrations in surficial (recently deposited) sediments of Puget Sound. Although contaminant levels in some areas of Puget Sound have been well characterized with data from many studies, other regions are poorly known. Also, despite source controls initiated in recent decades, some areas remain highly contaminated and thus pose a serious threat to the marine and estuarine ecosystems of Puget Sound.

Despite the availability of data on sediment quality from many studies and regions of Puget Sound, none of these historical data were collected with methods that allowed estimates to be made of the surficial or spatial extent of degradation. Often, studies were performed in the vicinity of specific point sources or other focused areas, thus precluding analyses of the data to determine the actual size and spatial dimensions of the degraded areas.

The National Oceanic and Atmospheric Administration (NOAA) conducts a nationwide program of monitoring and bioeffects assessments via the National Status and Trends (NS&T) Program. NOAA is authorized to conduct this research under Title II of the Marine Protection, Research, and Sanctuaries Act. NOAA has conducted research in numerous bays and estuaries along the Atlantic, Gulf of Mexico, and Pacific coasts in the NS&T Program. In 1997 NOAA elected to include the Puget Sound area in the program. Washington State enacted legislation in 1996 that specifically requires the Puget Sound Water Quality Action Team to ensure continued implementation and coordination of the Puget Sound Ambient Monitoring Program (PSAMP). Through this program, the state is required to monitor and assess the environmental health of Puget Sound. In 1997 NOAA and Washington Department of Ecology entered into the first year of a planned three-year agreement to study adverse biological effects of toxins, such as those found in sediments, in Puget Sound.

The overall goals of this program are to provide information on the presence, severity, and spatial extent of adverse biological effects attributable to toxic chemicals. Data to be generated in this program are intended to be used to estimate the overall environmental health of Puget Sound, to record changes in sediment quality over time as source controls are implemented, to identify areas most in need of source controls and other management actions, and to rank potentially toxic substances of greatest concern. Specific objectives of the program in Puget Sound are:

1. Estimate the spatial extent of chemical contamination, toxicity, and benthic community alterations in surficial sediments;
2. Identify spatial patterns in chemical concentrations, toxicity, and benthic community alterations (possibly leading to the identification of hot spots);
3. Determine the incidence and severity of sediment toxicity;
4. Estimate the apparent relationships between toxicant concentrations and measures of sediment toxicity;
5. Compare and rank the quality of sediment among different regions of Puget Sound; and

6. Determine the temporal trends in contaminant levels and prevalence of liver disease in selected resident demersal fishes.

The purpose of this paper is to outline the methods being used in this program and to document initial results of the toxicity tests performed in northern Puget Sound during 1997. Equivalent research is planned for central Puget Sound in 1998 and for southern Puget Sound in 1999.

Methods

To provide estimates of the spatial extent of sediment degradation, data must be representative of and attributable to the areas in which samples are collected. That is, station location coordinates must be chosen randomly, wherein all candidate longitude/latitude intersections have the same probability of being selected. To provide information on spatial patterns, if any, of sediment degradation, samples must be collected across suspected or known pollution gradients. To determine relationships between measures of contamination and toxicity, chemical analyses and toxicity tests must be performed on portions (aliquots) of the same samples taken synoptically (at the same time). To compare and rank sampling stations based upon a weight of chemical and toxicological evidence, data are needed from a battery of chemical analyses and toxicity tests. The study design selected for this study was intended to satisfy all of these requirements.

The study area chosen extended from the U.S./Canada border south to Port Gardner and Everett Harbor (Figure 1). Emphasis was placed upon four urban areas: Blaine, Bellingham, Anacortes, and Everett where—based upon previous studies—pollution gradients were most likely. Within the selected study area, 33 sampling strata were identified. Strata boundaries were identified as physiographic features expected to have relatively homogenous sedimentological and pollution properties. For example, in bays such as Drayton Harbor and Birch Bay, the strata were identified as a line across the mouth of bay to the 6 ft. isobath. In open-water areas such as the area south of Boundary Bay, the region was arbitrarily subdivided into roughly equal-sized polygons. Strata were invariably smaller in urban bays where toxicants were expected to occur in heterogeneous or transitional patterns, and, thus, where a denser sampling grid was needed. In areas more distant from urban centers, and, where, therefore, relatively homogeneous, non-polluted conditions were expected, the strata were larger.

Initially, the study plan included Guemes Channel as stratum 20 (Figure 1). However, only rocks and boulders were encountered in this stratum, therefore it was excluded from the study area.

After the dimensions of the strata were determined in discussions between NOAA and Ecology, coordinates of candidate station locations were determined with a computer-aided (NOAA GINPRO) random process. Four alternative locations were determined for each station. The sampling vessel was maneuvered to the first alternative with the aid of differential-corrected GPS. If it was infeasible to sample the first alternative because of obstructions or lack of sediments, the second, third, or fourth alternatives were used.

Sediments were collected in a double van Veen grab sampler following strict criteria for sample acceptance and rejection. Surficial material (upper 2–3 cm) was removed with cleaned high-density plastic scoops and placed in a high-density, polyethylene bucket. The sampler was deployed several times at each station to obtain 7–8 liters of sediment. The composited sample was then homogenized with a paddle. Portions necessary for four toxicity tests and chemical analyses were removed from the composited sample. All sampling equipment was cleaned with ambient seawater, soap, solvent and seawater between stations. Benthic samples were collected with separate deployments of the sampler at each station.

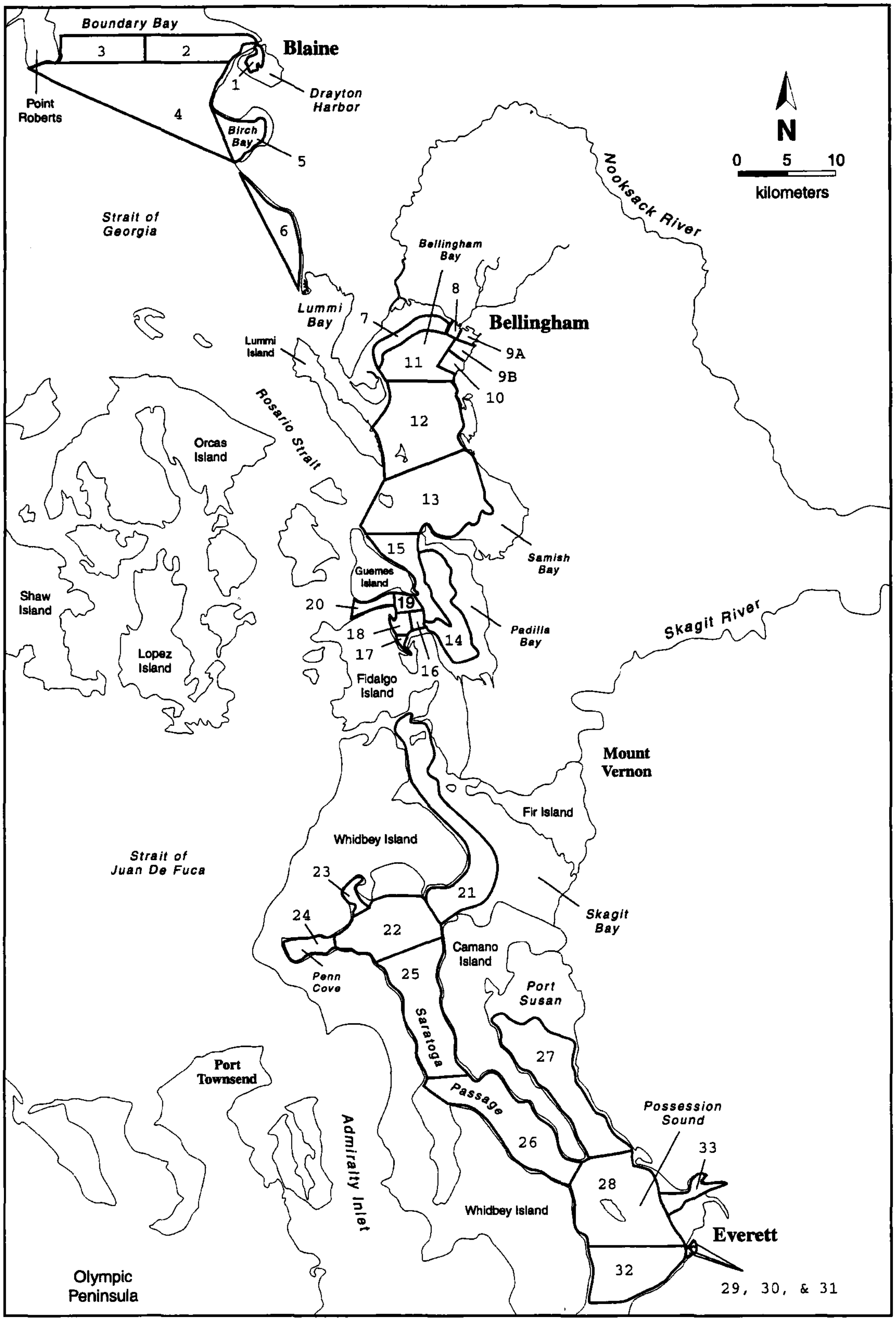

Figure 1. Locations and dimensions of sampling strata within the northern Puget Sound study area.

Toxicity tests were performed with widely accepted protocols. Amphipod survival tests followed protocols of the ASTM (1993), using the species *Ampelisca abdita*. Tests were performed with *A. abdita* in

surveys performed in areas along the Atlantic and Gulf of Mexico coasts and as a part of the Environmental Monitoring and Assessment Program (EMAP) estuaries studies (Long et al., 1996). Percent survival in five replicates of 20 animals each was determined after 10-day exposures. Tests of amphipod survival were performed for NOAA by Science Applications International Corporation, as in many previous surveys. This test is regarded as a widely accepted bioassay of relatively unaltered sediments in which acute toxicity is measured with an ecologically-important and relatively sensitive taxonomic group.

Sea urchin fertilization tests followed protocols of the U. S. Geological Survey (USGS) (Carr and Chapman, 1992), using gametes of the purple urchin, *Strongylcentrotus purpuratus*. Pore waters were removed from sediments with gentle pressure, captured in glass, pre-cleaned vials, frozen, thawed and tested in 100%, 50%, and 25% porewater concentrations. Sperm cells were exposed to the porewaters for one hour. Percent fertilization success as determined by the presence of a fertilization membrane around the eggs was determined in five replicates for each sample. These tests were performed by USGS for NOAA, as in numerous other areas. They provide information with a highly sensitive early life stage (sperm cells) exposed to porewaters, the phase in which sediment-associated toxicants are expected to be highly bioavailable.

Cytochrome P-450 assays of the light produced by luciferase in a reporter gene system (RGS) of cultured human liver cells was conducted on all of the samples collected during 1997. In these tests, standard protocols (Anderson et al., 1995, 1996; ASTM, 1997; APHA, 1996) were followed to ensure comparability with data derived from other areas. Approximately 20 g of sediment from each station were extracted with dichloromethane (DCM) to produce 1 mL of DCM containing organic compounds. Small portions of these samples (2–10 µL) were applied to approximately one million human liver cells contained in three replicate wells with 2 mL of culture medium. After 18 hours of incubation, the cells were washed, then lysed, and the solution centrifuged to produce 50 µL extracts. Small portions (10 µL) were used in measures of luminescence. The relative light unit (RLU) from the solvent blank was set equal to unity and all other RLUs were divided by (normalized to) that of the blank. The running average fold induction for 10 nM dioxin is approximately 140 and the induction from 1 µg/mL of benzo(a)pyrene (b[a]p) was 60-fold. Data were converted to mg of b(a)p equivalents per g of sediment. The assay has been performed for NOAA by Columbia Analytical Services, Inc. (CAS) and is responsive to the presence of mixed-function oxidase inducers such as dioxins, furans, high molecular weight PAHs, and coplanar PCBs in tissues and sediments (Anderson et al., 1995).

Microbial bioluminescence (Microtox™) tests were performed with protocols initially developed for Puget Sound (US EPA Region 10, 1990; Schiewe et al., 1985). These tests were run on a portion of the extracts prepared by CAS for the cytochrome P-450 assays. Tests were run in duplicate over a dilution series to determine the EC50 values (the concentrations of sediments that caused a 50% reduction in bioluminescence). USGS in Columbia, MO performed these tests for NOAA, using the same protocols previously used nationwide by USGS and the National Marine Fisheries Service in Charleston, SC. Microtox tests are highly sensitive indicators of the presence of potentially toxic substances in sediments regardless of their bioavailability.

Results of amphipod survival and sea urchin fertilization tests for each sample were compared to those for negative controls to assign statistical significance. In the amphipod tests, sample means were compared to means of tests of a Central Long Island Sound (NY) control previously used in many surveys by SAIC. In the sea urchin tests, sample means were compared to means for controls from Redfish Bay, Texas—an area previously tested by the USGS. Results from the Microtox and cytochrome P-450 tests are currently undergoing review; therefore, calculations of the spatial extent of toxicity are not yet available.

Toxicity data were assigned one of three levels of statistical significance: not significant, significant, or highly significant. When sample means were not significantly different from control means ($p>0.05$), they were classified as not significant (i.e., non-toxic). Samples were classified as significant (i.e., "toxic") when sample means were significantly different ($p<0.05$), but sample means were more than 80% of control means. Highly toxic samples were those in which sample means were significantly different from controls and less than 80% of controls. The critical value used in the estimates of the spatial extent of toxicity was <80% of controls.

The cumulative frequency distributions of the data were determined by arranging the data in order of descending toxicity. Data from each station were weighted to the sizes of the strata they represented. Spatial extent of toxicity was calculated as the sums of the sample-weighted strata in which the mean toxicity response was less than 80% of controls (Long et al., 1996).

Results

Results of the cytochrome P-450 RGS assay showed relatively non-toxic conditions in most of the 100 samples. The highest responses came from stations clustered within inner Everett Harbor. Figures 2 and 3 show a clear pattern in induction activity among samples collected at stations within and near Everett Harbor. Highest induction activity occurred in the sample from Station 86 (104.6 µg/kg benzo(a)pyrene equivalents) which was collected in Stratum 29 in the inner reaches of the harbor. Toxicity diminished to 33.1 and 52.7 µg/kg B(a)p equivalents in Stations 87 and 88, respectively, within the same stratum, and again to 25–34 µg/kg in samples from Stratum 30, and again to 25–30 µg/kg in samples from Stratum 31 in Port Gardner Bay. Toxicity decreased again among the stations in the outer reaches of Port Gardner Bay (Figure 3).

In the amphipod tests, mean survival ranged from 93% to 99% in the CLIS controls, well within the range of acceptability. Reference toxicant test LC50s ranged between 2.16 to 7.86 mg/L sodium dodecyl sulfate (SDS)—within the acceptable ranged for 10 of 11 test series. Mean survival in test samples, normalized to respective controls, indicated a relatively small range in response—from 82% to >100%.

Mean amphipod survival in sediments from 13 of the 100 stations was significantly different from controls. Thus, the incidence of toxicity was 13%. Three of the stations with significant results were in Strata 2 and 4 south of Boundary Bay, one each was in Strata 10 and 9B in outer Bellingham Bay, one was in Samish Bay, one in outer Padilla Bay, one in Stratum 21 in south Skagit Bay, one in outer Oak Harbor, one in Penn Cove, two in Everett Harbor, and one in the mouth of the Snohomish River.

However, statistical analyses of sample and control means that have very low within-sample variance can show significant differences even when numerical differences between means are very small. The use of the MSD values provides a more rigorous criterion for classifying samples as "toxic," and, therefore, for classifying samples as actually toxic (Thursby et al., 1996). None of the results indicated mean survival was less than 80% of controls. Therefore, the spatial extent of toxicity in the amphipod survival tests was 0% (Table 1).

Table 1. Estimated spatial extent of sediment toxicity in tests of amphipod survival and sea urchin fertilization performed on 100 samples from northern Puget Sound.

Toxicity test	Toxic area (km^2)	Percent of total*
Amphipod survival	0.0	0.0
Urchin fertilization		
• 100% pore water	40.6	5.2
• 50% pore water	11.5	1.5
• 25% pore water	5.9	0.8

* total area: 773.9 km^2

Fertilization success in 100% pore water from the negative controls was 80.6%, 84.6%, and 95.2% in three test batches. Tests of SDS positive controls resulted in EC50s of 2.73–3.11 mg/L SDS. All data were acceptable. In tests of 100% pore water, mean test results normalized to negative controls ranged from 0% fertilization success in several samples to >100%. In tests of 100% pore waters, mean fertilization success was significantly reduced in 15 of the 100 samples; thus, resulting in 15% incidence of toxicity. Based upon the same criteria as in the amphipod tests, the spatial extent of waters (Table 1).toxicity was 5.2% in tests of 100% pore waters, 1.5% in 50% pore waters, and 0.8% in 25% pore waters.

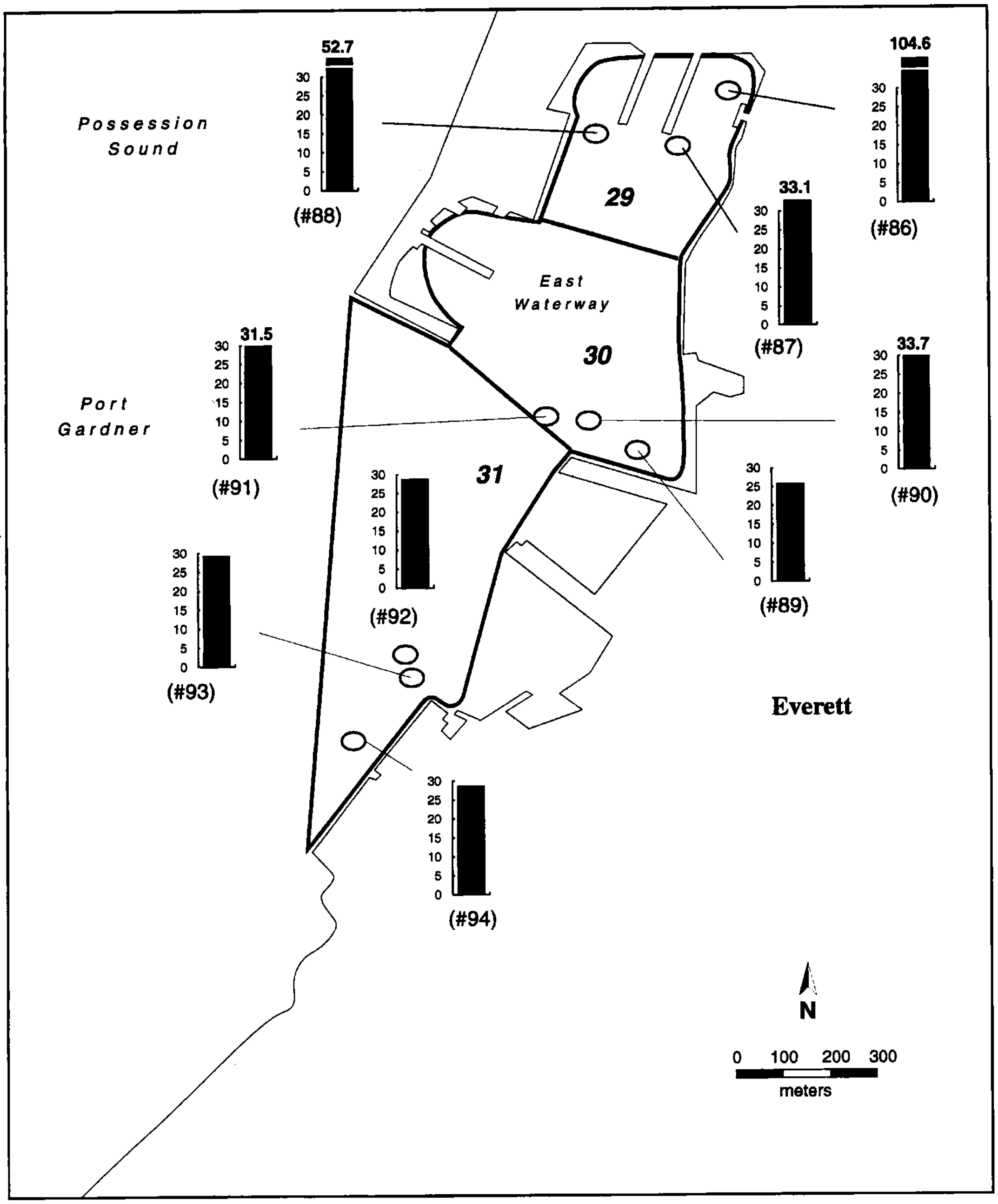

Figure 2. Results of cytochrome P-450 RGS assays of sediments from station in Everett Harbor vicinity (data expressed as µg/kg benzo(a)pyrene equivalents).

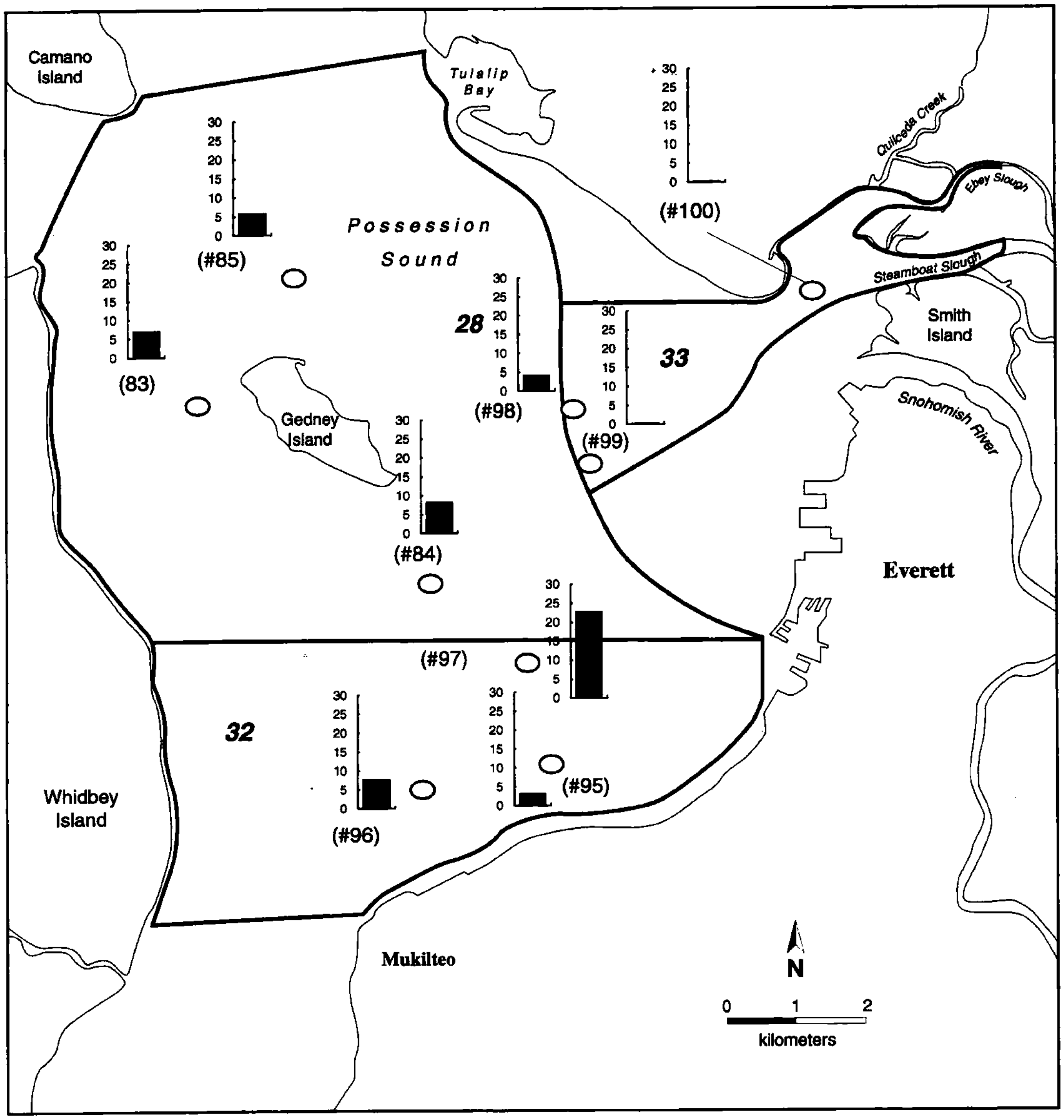

Figure 3. Results of cytochrome P-450 RGS assays of sediments from stations in Port Gardner Bay (data expressed as "µg/kg benzo(a)pyrene equivalents).

All nine of the samples from Everett Harbor were highly toxic in tests of 100% pore waters; four of them were highly toxic in tests of both 50% and 25% porewater concentrations. Other samples that were toxic came from Port Susan, Fidalgo Bay, Padilla Bay, Bellingham Bay (one station each), and Drayton Harbor (two stations). Toxicity was most severe in the samples from Drayton Harbor and outer Everett Harbor where fertilization success was 0% to 5% in tests of 100% pore waters.

Discussion and Conclusions

The incidence, severity, and spatial extent of toxicity has been determined in sediments from many different bays and harbors along the Atlantic, Pacific, and Gulf of Mexico coasts (Long et al., 1996). In these surveys, protocols and methods equivalent to those used in Puget Sound were used to ensure comparability of the data. Much of the data was generated by the same laboratories, using the same sources of test animals and controls. To provide perspective to the results from northern Puget Sound,

the data from Puget Sound are compared to those from other areas (Tables 2–3).

Comparable data from amphipod survival tests are available from 24 areas, including northern Puget Sound (Table 2). Except in California where *Rhepoxynius abronius* was used, tests were performed with *Ampelisca abdita.* Surficial extent of toxicity ranged from 0% in many areas to 85% in Newark Bay. The "national averages" calculated with data accumulated after the 1995 surveys (Long et al., 1996) and, again, in 1996 are shown along with the data from each individual area. The samples from northern Puget Sound rank among the least toxic; one of 12 areas with 0% toxicity and well below the national averages of 10.9% in 1995 and 6.9% in 1996. Additional data from US EPA studies performed as a part of the Environmental Monitoring and Assessment Program (EMAP) showed that the surficial areas of toxicity were 0% within the Californian province, 8.4% in the Louisianian province, 2% in the Carolinian province, and 10% in the Virginian province (Long et al., 1996).

Table 2. Spatial extent of toxicity (km^2 and percentages of total area) in amphipod survival tests performed with solid-phase sediments from 24 US bays and estuaries.

				Amphipod survival	
Survey Areas	Year sampled	No. of samples	Total area (km^2)	Toxic area (km^2)	Percent of total area
Newark Bay	93	57	13	10.8	85.0%
San Diego Bay	93	117	40.2	26.3	65.8%
California coastal lagoons	94	30	5	2.9	57.9%
Tijuana River	93	6	0.3	0.18	56.2%
Long Island Sound	91	60	71.86	36.3	50.5%
Hudson-Raritan Estuary	91	117	350	133.3	38.1%
San Pedro Bay	92	105	53.8	7.8	14.5%
Biscayne Bay	95/96	226	484.2	62.3	12.9%
National average: 1995		**1274**	**2532.6**	**277.00**	**10.9%**
Boston Harbor	93	55	56.1	5.7	10.0%
National average: 1996		**1470**	**4158.1**	**286.40**	**6.9%**
Savannah River	94	60	13.12	0.16	1.2%
St. Simons Sound	94	20	24.6	0.10	0.4%
Tampa Bay	92/93	165	550	0.5	0.1%
Galveston Bay	96	75	1351.1	0.0	0.0%
northern Puget Sound	97	100	773.9	0.00	0.0%
Pensacola Bay	93	40	273	0.04	0.0%
Choctawhatchee Bay	94	37	254.47	0	0.0%
Sabine Lake	95	66	245.9	0.00	0.0%
Apalachicola Bay	94	9	187.58	0	0.0%
St. Andrew Bay	93	31	127.2	0	0.0%
Charleston Harbor	93	63	41.1	0	0.0%
Winyah Bay	93	9	7.3	0	0.0%
Mission Bay	93	11	6.1	0.0	0.0%
Leadenwah Creek	93	9	1.69	0	0.0%
San Diego River	93	2	0.5	0.0	0.0%

Sea urchin fertilization tests were performed with *Arbacia punctulata* obtained from the Gulf of Mexico in most areas. In California, gametes of *Strongylocentrotus purpuratus* or embryos of abalone *Haliotis rufescens* were used in the porewater tests. In the sea urchin tests performed with 100% pore waters, northern Puget Sound ranked among the least toxic areas (Table 3). The national averages calculated with data accumulated through 1995 and 1996 were 42.6% and 38.7%, respectively. In contrast, the results for northern Puget Sound showed the spatial extent of toxicity was about 5.2%. Only three other areas showed less toxicity in this test.

Table 3. Spatial extent of toxicity (km^2 and percentages of total area) in sea urchin fertilization tests performed with 100% sediment pore waters from 23 US bays and estuaries.

				Urchin fertilization @100%	
Survey areas	Year sampled	No. of samples	Total area (km^2)	Toxic area (km^2)	Percent of total area
San Pedro Bay	92	105	53.8	52.6	97.7%
Tampa Bay	92/93	165	550	463.6	84.3%
San Diego Bay	93	117	40.2	25.6	76.0%
Mission Bay	93	11	6.1	4.0	65.9%
Tijuana River	93	6	0.3	0.18	56.2%
San Diego River	93	2	0.5	0.26	52.0%
Biscayne Bay	95/96	226	484.2	229.5	47.4%
Choctawhatchee Bay	94	37	254.47	113.14	44.4%
California coastal lagoons	94	30	5	2.1	42.7%
National average: 1995		**940**	**2082.6**	**886.3**	**42.6%**
Winyah Bay	93	9	7.3	3.1	42.2%
National average: 1996		**1136**	**3723.26**	**1439.73**	**38.7%**
Apalachicola Bay	94	9	187.58	63.6	33.9%
Galveston Bay	96	75	1351.1	432.0	32.0%
Charleston Harbor	93	63	41.1	12.5	30.4%
Savannah River	94	60	13.12	2.42	18.4%
Boston Harbor	93	55	56.1	3.8	6.6%
Sabine Lake	95	66	245.9	14.0	5.7%
Pensacola Bay	93	40	273	14.4	5.3%
northern Puget Sound	97	100	773.9	40.6	5.2%
St. Simons Sound	94	20	24.6	0.65	2.6%
St. Andrew Bay	93	31	127.2	2.28	1.8%
Leadenwah Creek	93	9	1.69	0	0.0%

In conclusion, data available thus far from the tests suggest that toxicity is not very severe or widespread in northern Puget Sound sediments. The surficial area in which acute toxicity to adult crustaceans was observed represented 0% of the total area, and the extent of toxicity in the sublethal fertilization test was very small—5% of the total. Cytochrome P-450 RGS assays showed highest induction mainly in samples from inner Everett Harbor. Microbial bioluminescence appeared to be most affected also in samples from Everett Harbor. Results from all four tests indicate that toxicity was most severe in inner Everett Harbor, and to a lesser extent in a few other urban bays such as Drayton Harbor and Bellingham Bay. Data from chemical analyses will be used to identify substances that may have contributed to toxicity. Data from benthic community analyses will be examined to determine if toxicity observed in laboratory tests is also expressed *in situ* among resident biota. Collectively, data from the chemical, toxicological, and benthic analyses will be compiled to provide an overall synopsis of sediment quality in northern Puget Sound.

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Spatial Trends in the Concentration of Polychlorinated Biphenyls (PCBs) in Chinook (*Oncorhynchus tshawytscha*) and Coho Salmon (*O. kisutch*) in Puget Sound and Factors Affecting PCB Accumulation: Results from the Puget Sound Ambient Monitoring Program

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Introduction

Polychlorinated biphenyls (PCBs) are among the most ubiquitous and persistent contaminants in aquatic ecosystems worldwide. Even though only an estimated 1% of the total PCBs produced have reached the oceans so far (Stone 1992), PCBs are everywhere in aquatic systems (Phillips 1964) including remote polar aquatic ecosystems where PCBs are transported via atmospheric processes (Hammar 1989). PCBs were manufactured prior to 1975 and used extensively as industrial coolants and in electrical transformers, where they were frequently mixed with oils and greases. Since 1976, PCB manufacture has been banned in the U.S., but they persist in the aquatic environment and their high toxicity continues to cause concern for aquatic life, especially fish.

The Washington Department of Fish and Wildlife (WDFW) monitors concentrations of 101 contaminants in marine fishes in Puget Sound, including chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*), as part of the Puget Sound Ambient Monitoring Program (PSAMP). This effort is implemented by a multi-agency consortium of scientists and natural resource managers who assess and monitor the environmental health of the Puget Sound ecosystem (Puget Sound Water Quality Authority 1995; Puget Sound Water Quality Action Team 1998). This monitoring has documented that PCBs are one on the few contaminants that accumulate in chinook and coho salmon from Puget Sound. WDFW continues to monitor PCB concentrations in adult chinook and coho salmon because of their importance in the Puget Sound ecosystem and in recreational and commercial fisheries. Prior to these PSAMP studies, PCB exposure and accumulation in chinook and coho salmon from Puget Sound were not well studied. The aim of PSAMP is to assess spatial and temporal trends in PCB exposure in these species by annually monitoring PCB concentrations in the edible muscle tissue of adult fish at various locations throughout Puget Sound.

Exposure to PCB-contaminated sediments and food are primary pathways for accumulation of PCBs in fish (Varanasi et al. 1992). However, various biotic and abiotic factors affect the degree of exposure and accumulation. Exposure to PCBs may be affected by the proximity of fish to contaminated sediments and prey, the magnitude of contamination in their habitats, fish movement patterns, trophic status, growth rates, duration of exposure (i.e., lifespan or fish age), and bioavailability of PCBs (Jensen et al. 1982; Hammar et al. 1993; Stow et al. 1994; Bentzen et al. 1996). Furthermore, although fish may be exposed to PCBs, species-specific metabolism and detoxification of PCBs, reproductive and maturational patterns (e.g., sex and age of first reproduction), and the level of body fat (i.e., percent lipids) can affect the degree to which these PCBs accumulate in tissues, and have adverse effects (Masnado 1987; Larsson et al. 1991; Varanasi et al. 1992; Loizeau and Abarnou 1994; Bentzen et al. 1996; Larsson et al. 1996).

In the Pacific Northwest PCBs have been detected in Pacific salmon from various locations in Alaska (NMFS unpublished data, John Stein, personal communication) and the Columbia River (Tetra Tech. Inc. 1996), suggesting a widespread source of PCBs in this areas. Pacific salmon are anadromous and throughout their lives may be exposed to PCBs in fresh water, estuarine, or marine areas. Although

specific migratory patterns of these species vary, chinook and coho salmon are spawned in freshwater, live there for 3 to 15 months after emergence as embryos from gravel nests, and subsequently migrate to marine waters. PCB concentrations in prey consumed by salmon may vary in these habitats. In fresh water, young chinook and coho salmon consume aquatic insects and crustaceans but as these fish smolt and enter the estuary they consume a wider variety of invertebrates and larval fish (Higgs et al. 1995). Adult salmon in marine waters continue to eat invertebrates but they consume more epipelagic fish (Higgs et al. 1995), increasing the likelihood of PCB biomagnification in their tissues. The amount of time each species or population spends at sea varies widely, but for both species the majority of their growth occurs in marine waters (Groot and Margolis 1991) before they return to their natal streams to spawn.

PCBs are lipophilic, typically concentrating in the fatty tissues in fishes (Varanasi et al. 1992), and thus PCBs may readily accumulate in muscle tissue of adult chinook and coho salmon because of their relatively high lipid content. However, the lipid content in the muscle tissue in adult salmon in marine waters decreases rapidly as they approach fresh water and reach reproductive maturity, particularly in females (Hendry 1998). Thus, the lipid content of the muscle tissue, the sex of the fish, and the degree of maturation may all affect PCB accumulation in chinook and coho salmon.

One of the main objectives of PSAMP is to assess species-specific and location-specific differences in PCB accumulation in adult chinook and coho salmon. However, meaningful comparisons of PCB concentration in tissues of chinook and coho salmon from different Puget Sound locations can only be made after an accounting of the factors described above that could affect PCB accumulation at these locations. The purpose of this paper was to model the accumulation of PCBs in chinook and coho salmon from Puget Sound. In addition to unspecified location effects that may be associated with proximity to and magnitude of PCB contamination, we estimated the contribution of percent body weight as lipids, the gender and age of the fish, and the hatchery or wild origins of the fish. First, we compared differences in PCB concentrations between adult chinook and coho salmon sampled from marine areas of Puget Sound and from five Puget Sound rivers. Then, for coho salmon we evaluated the effects of tissue lipid content and sampling location on PCB accumulation. At a subset of the sampling locations we evaluated the effects of gender and the hatchery or wild origins on the PCB accumulation in coho salmon. An insufficient number of samples was collected to fully assess which aspects of the chinook salmon's complicated life history affect PCB accumulation in that species, and therefore only preliminary analysis on the effects of fish age and percent lipids are presented for that species in this paper.

Materials and Methods

Sample Locations and Preparation

Adult chinook and coho salmon were sampled from five "in-river" locations (including near-shore estuarine and river locations) where the captured fish were presumed to be returning to their natal streams and various offshore "marine" locations in central and southern Puget Sound where the fish's natal stream was unknown (Figure 1). Fish were purchased from licensed fish buyers and treaty tribal fishermen in the late summer and early fall of 1992–1995. Nooksack, Skagit and the Duwamish/Green rivers were sampled in all years but the Nisqually and Deschutes rivers were only sampled in 1993, 1994, and 1995. Whole salmon were transported on ice to the laboratory where we tagged, measured (fork length, nearest cm), weighed and then removed some of their scales for age-estimation (detailed below). The fish were then wrapped individually in aluminum foil, placed in plastic bags and stored on ice for up to 10 days until tissues were removed for contaminant analyses.

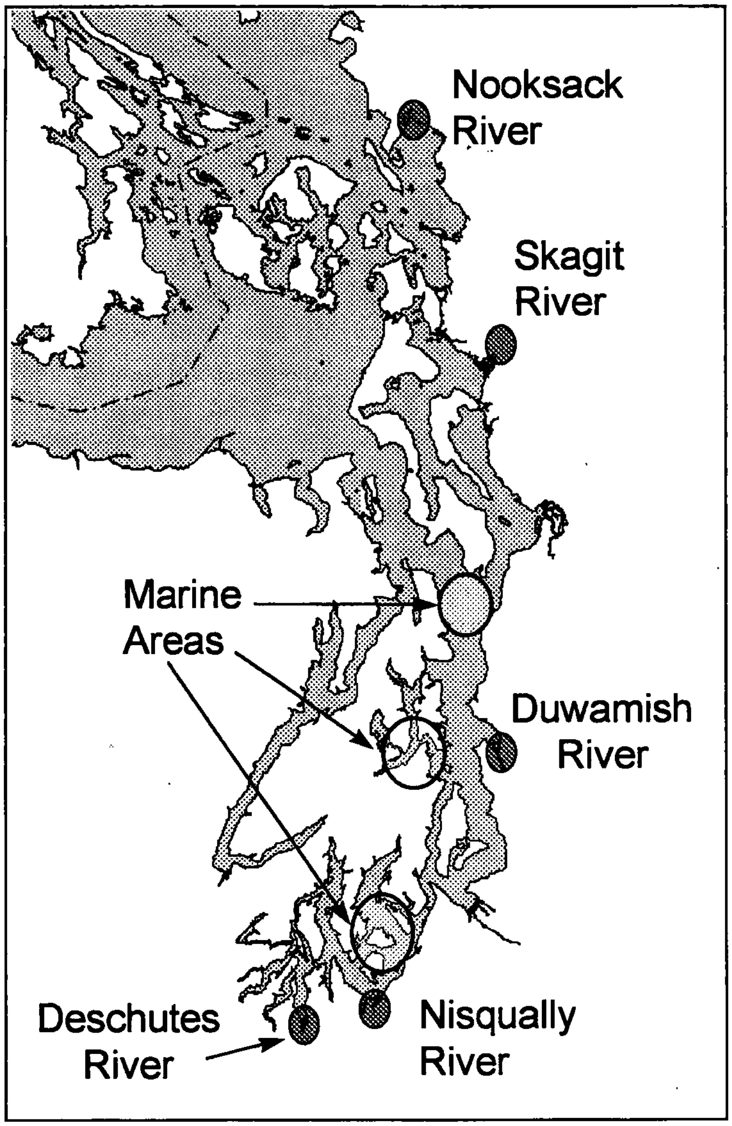

Figure 1. Five in-river and three marine locations sampled by PSAMP for coho and chinook salmon, 1992–1995.

Composite muscle tissue samples of chinook and coho salmon were prepared by collecting equal amounts of skinned muscle tissue from individual fish and combining the tissue in pre-cleaned jars to make one composite sample as detailed in the Puget Sound Estuary Program protocols (Puget Sound Estuary Program 1986). Utensils and work surfaces were cleaned and then rinsed with isopropyl alcohol between each sample. Muscle tissue composites were frozen at -20_ C. prior to analysis. The number of fish comprising a composite varied from one to five individuals among years. In 1992 and 1993, fish from an individual location were composited randomly, without regard to sex, fish age or hatchery or wild origin, but in 1994 and 1995, fish of like sex and origin were combined in composites. A minimum of six composite samples was prepared for each species per sampling location per year.

The pattern and spacing of circuli on the scales were used to estimate the total age of the fish and the year in which the fish migrated to sea. For example, a coho salmon that went to sea in its second year and returned to spawn in its third year had a freshwater age of two, and a total age of three (designated 3_2). A four-year-old chinook that went to sea in its first year of life and had a freshwater age of one

would be designated 4_1. Also, for those fish that went to sea in their second year, the pattern of growth rings was used to classify the fish as hatchery or wild in origin.

Chemical Analyses

Chemical analyses for PCBs were completed according to PSEP protocols (Puget Sound Estuary Program 1996b). Briefly, all tissue samples delivered to the chemical laboratory were homogenized in a blender and PCBs were extracted from fish samples by sonication with a methylene chloride and acetone mix. All extracts were "cleaned" by gel permeation chromatography. PCBs were analyzed using gas chromatography-electron capture detection (GC/ECD), with a dual narrow-bore column (0.25 mm) suited to analyzing low concentrations (1992,1993, and 1994), or with an ion trap detector (1995) . Aroclor mixtures were used as standards for quantifying PCB concentrations. Matrix-based detection limits were determined for the muscle tissue by adding standards to representative instrument-ready sample matrices. All chemistry data were reported as the concentration per wet weight of tissue in g/kg (ppb).

Lipids were determined by a modified crude fat determination using acid hydrolysis. The tissue sample was mixed with sodium sulfate, extracted with a sonic probe using a mixture of methylene chloride and acetone, filtered through a bed of sodium sulfate powder, and the solvent was allowed to evaporate. Percent lipids were then determined gravimetrically and reported as percent of total weight.

Quality Assurance and Quality Control (QA/QC)

An independent QA/QC chemist reviewed tissue chemistry data and detailed findings were presented to WDFW. In general, the QA/QC chemist reported that the chemical laboratory followed the PSEP protocols for chemical analyses of organic contaminants in fish tissue (Puget Sound Estuary Program 1996b) and produced good quality data on PCB concentrations in chinook and coho salmon.

Data Analyses

The percent lipids and the mean fish age were computed for the fish comprising each composite sample. All statistical analyses on lipid-specific PCB concentrations were conducted using Mean Composite Age (MCA), and Composite Percent Lipids (CPL).

A two-way Analysis of Variance was used to assess whether observed PCB concentrations varied significantly between chinook and coho and between marine- and river-caught fish within a species. For coho salmon, linear regression analysis was used to model accumulation of PCBs in coho in marine waters and in fish returning to Puget Sound rivers, with stepwise (forward) variable selection (Kleinbaum and Kupper 1978). Variables modeled included CPL and dummy variables that were used to estimate location-specific variability in tissue contaminants. A t-test of log-normalized PCB data was used to test the significance of differences in PCB means between marine-caught coho salmon from central Puget Sound and south Puget Sound.

Because of limited sampling size, variation associated with the hatchery or wild origin status and the sex of the fish (gender) could not be assessed for coho at all locations. For those stations with sufficient sample sizes and ranges of lipid values, wild and hatchery fish were analyzed separately using linear regression to estimate the contribution of lipid content and sampling location on PCB accumulation. Dummy variables were used to estimate the location effect in lipid-specific PCB concentrations.

The potential effects of fish gender on lipid-specific PCB-accumulation, separate from effects associated with location or the hatchery or wild origins, were assessed by analyzing wild coho salmon samples from the Deschutes River with linear regression. Variables in the model included percent lipids and a dummy variable for sex.

Linear regression analysis with log-normalized lipid data was used to model the relationship between PCBs and CPL for chinook salmon. Data from all locations were combined for that species.

Results

From 1992 to 1995, we collected 178 chinook and 157 coho composite-samples from adult fish from five in-river locations and from several marine locations in Puget Sound. PCBs were detected in both salmon species from both location types. Chinook salmon·from marine locations had the greatest mean concentration of PCBs (74.2 µg/kg), followed by chinook salmon from in-river locations (49.1µg/kg), coho salmon from marine locations (35.1 µg/kg), and coho salmon from in-river locations (26.5 µg/kg; Figure 2, Table 1).

Table 1. Average total PCB concentrations (µg/kg) in coho and chinook salmon sampled from in-river and marine location types. Sample sizes in parentheses.

	Location Type		
Species	Marine	In-River	Grand Mean
Chinook	74.2 (34)	49.1 (144)	53.9 (178)
Coho	35.1 (32)	26.5 (125)	28.3 (157)
Grand Mean	55.3 (66)	38.6 (269)	41.85 (335)

Each of these differences was statistically significant; that is, the mean concentration of PCBs for each species-location combination was significantly different from the others (two-way analysis of variance using log-transformed PCB data, p=0.05 for species-location interaction). In addition, the average concentration of PCBs in chinook salmon (controlling for the effects of location type) type was significantly greater than coho salmon (53.9 µg/kg versus 28.2 µg/kg; p<0.001; Figure 2 and Table 1), and the average concentration of PCBs in salmon from marine locations (controlling for the effects of species) was significantly greater than in-river locations (55.3 µg/kg versus 38.6 µg/kg; p<0.001; Figure 2 and Table 1).

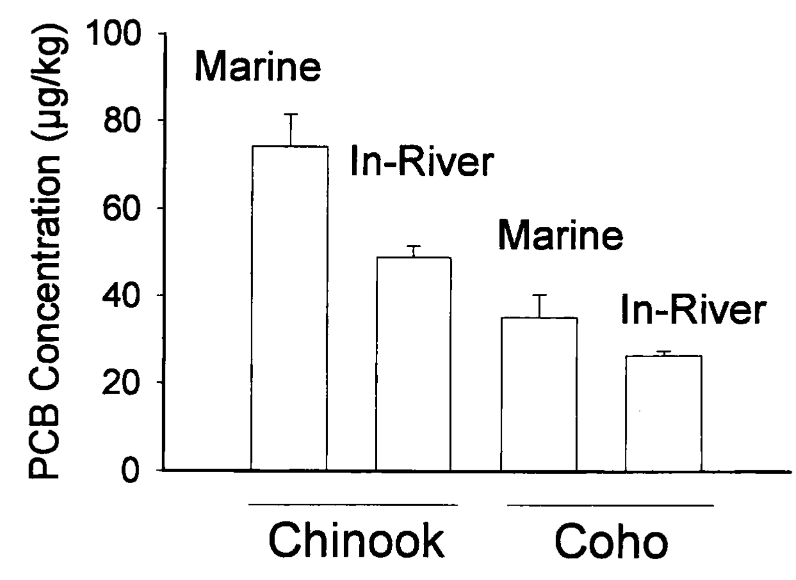

Figure 2. Average total PCB concentration (with standard errors) for chinook and coho salmon in marine and in-river locations of Puget Sound, 1992–1995.

Coho Salmon

We evaluated or attempted to control for the effects of four important potential factors on PCB accumulation in coho salmon; composite percent lipids (CPL), location, hatchery/wild origin, and

gender. Variability in fish age was not an important factor for coho salmon. All individual coho salmon we sampled were three-year-olds that went to sea in their second year, which was typical of most coho salmon returning to spawn in Puget Sound streams.

We observed a significant, positive correlation of total PCBs with CPL for four in-river locations (Figure 3a). Using forward stepwise linear regression analysis and dummy variables to isolate location effects, CPL and sampling location accounted for 61% of the total variation in these PCB concentration data (CPL transformed using natural log, $p<0.001$). Slopes of fitted regression lines were equal among locations, however, intercepts for Deschutes and Nisqually Rivers were significantly greater than for Skagit and Nooksack Rivers. This means that the pattern of PCB increase with CPL was the same for all locations. However, for a given CPL, PCB concentrations were highest in coho salmon from the Nisqually River, followed by coho from the Deschutes River (southern Puget Sound locations), and the Skagit and Nooksack rivers (northern Puget Sound locations; Skagit and Nooksack regression lines were coincident).

PCBs in coho salmon from the Duwamish Waterway did not exhibit a significant correlation with CPL as did the other four in-river locations (scatterplot omitted from Figure 3a). Mean PCB concentration of samples from the Duwamish Waterway (in central Puget Sound) independent of lipids was 27.3 µg/kg, which was intermediate between the southern locations (Deschutes and Nisqually rivers; 30.8 and 29.6 µg/kg) and the northern locations (Skagit and Nooksack rivers; 25.1 and 20.1 µg/kg).

Like the in-river locations, PCB concentrations in coho salmon sampled from marine locations from central Puget Sound were positively correlated with CPL (Figure 3b, $r^2=0.32$, $p=0.007$). However, those from marine locations in southern Puget Sound were not (Figure 3b, $p>0.05$). Because CPL apparently did not contribute to variability in the southern Puget Sound samples, we ignored that factor in comparing PCB concentrations between the two marine locations. Average PCB concentrations in southern Puget Sound samples (60.6 µg/kg) were significantly greater than central Puget Sound marine-caught samples (35.1 µg/kg; t-test of log-normalized PCB data, $p<0.001$). Eight of twelve southern Puget Sound samples exceeded the greatest PCB concentration from central Puget Sound (Figure 3b).

In addition to location-specific effects, the origin (whether wild or hatchery) may have contributed to variability in PCB concentration. The samples used to describe fish location-specific variation in PCB concentration for coho salmon (Figure 3) were composed of 55 wild, 50 hatchery and 52 mixed-origin samples. To evaluate potential influence of origin on PCB concentration, we re-plotted the relationship between PCBs and CPL presented in Figure 3a for wild and hatchery-origin coho salmon separately (Figure 4). Sample sizes and ranges of CPL were sufficient to model location-specific PCB:CPL relationships for wild-only coho salmon from three in-river locations (Deschutes, Nisqually, and Skagit rivers, Figure 4a), and hatchery-only coho salmon from two locations (Nisqually and Nooksack rivers, Figure 4b).

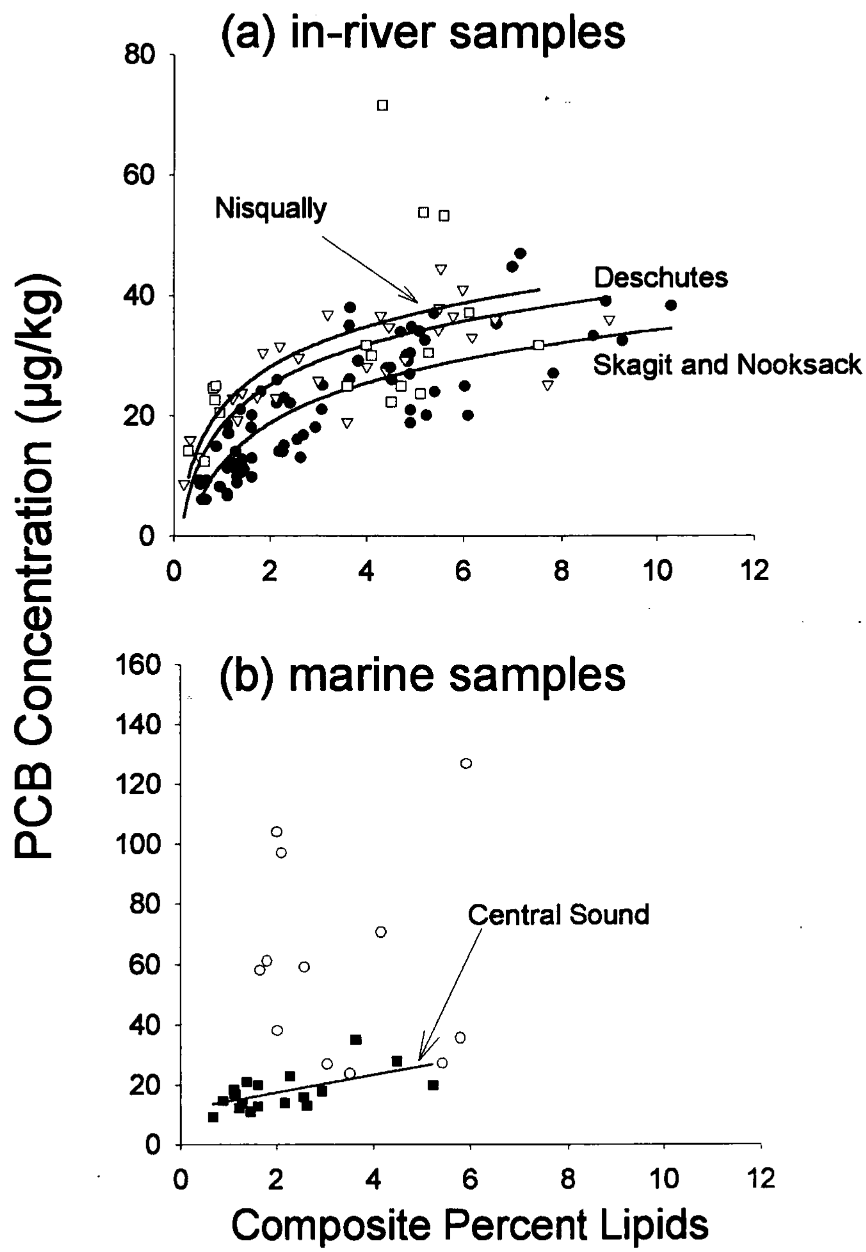

Figure 3. Relationship between total PCBs and tissue lipid content for coho salmon sampled from (a) in-river locations: Nisqually River (open squares), Deschutes River (open triangles), and combined Skagit and Nooksack Rivers (filled circles) and (b) marine locations: central Puget Sound (filled squares) and southern Puget Sound (open circles). Lipid data were log-transformed to linearize data for in-river samples. Forward stepwise linear regression analysis using dummy variables to isolate location effects was used to compute correlations and generate regression lines shown.

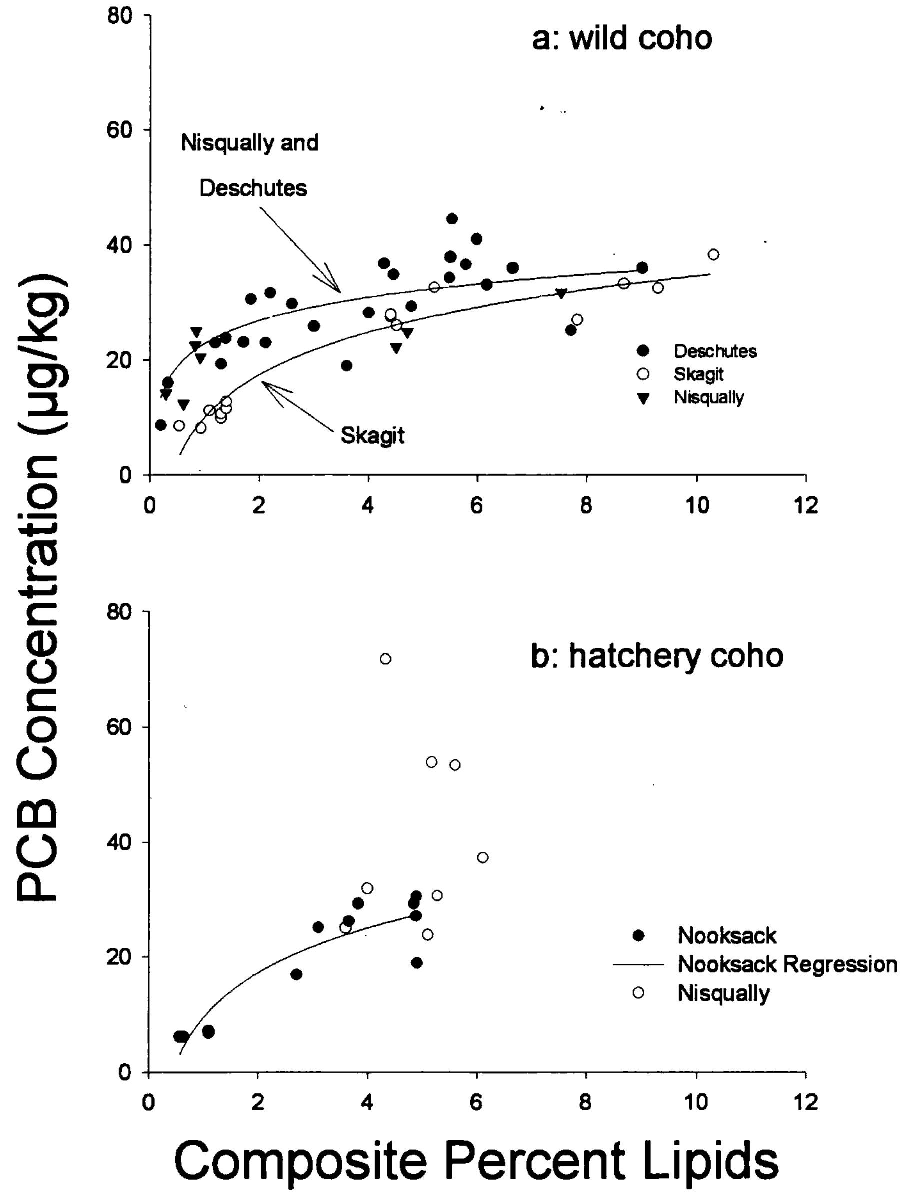

Figure 4. Relationship between total PCBs and tissue lipid content for (a) wild and (b) hatchery coho salmon from in-river locations. Forward stepwise linear regression analysis with log-linearized lipid data and dummy variables was used to estimate correlation coefficients and generate regression lines. Lines for wild Nisqually and Deschutes coho salmon were coincident (not significantly different from each other). The PCB:lipid correlation for Nisqually hatchery coho was not significant (p>0.05).

Wild-only coho salmon exhibited a strong correlation between PCBs and CPL, and the north-to-south gradient of increasing CPL-specific PCB concentrations was consistent with that previously observed for the combined wild and hatchery coho (Figure 4a, $r^2=0.64$, $p<0.001$). However, for hatchery-only coho salmon, we observed a strong correlation ($r^2=0.83$, $p<0.0001$) between PCBs and CPL for Nooksack River fish but not for coho from the Nisqually River ($p>0.05$, Figure 4b). Unexplained variability in lipid-specific PCB concentration for these hatchery coho salmon from the Nisqually River was similar to that observed for the coho from the Duwamish River (not shown). At the Duwamish location, samples consisted mostly of hatchery or mixed hatchery/wild origin fish (Table 2).

Thus, some hatchery fish, especially those from central and southern Puget Sound, appear to accumulate PCBs differently than wild coho salmon.

Table 2. Number of composite tissue samples collected from adult coho salmon from in-river and marine locations in Puget Sound, 1992–1995.

Location Type	Station	Wild-Origin Male	Wild-Origin Female	Wild-Origin Mixed Sex	Hatchery-Origin Male	Hatchery-Origin Female	Hatchery-Origin Mixed Sex	Mixed-Origin Male	Mixed-Origin Female	Mixed-Origin Mixed Sex
In-river	Nooksack River	1	1	1	5	2	5	3	0	7
	Skagit River	5	2	7	3	1	1	2	0	6
	Duwamish River	0	1	1	8	2	4	1	1	7
	Nisqually River	1	1	6	3	2	3	0	0	2
	Deschutes River	11	10	7	n/a	n/a	n/a	n/a	n/a	2
Marine	Central Sound	0	0	0	0	0	5	1	0	14
	Southern Sound	0	0	0	4	2	0	4	0	2

To further investigate potential effects of hatchery/wild origin without interference from unexplained location effects, we compared PCB accumulation between hatchery- and wild-origin coho salmon at a single location, the Nisqually River (Figure 5). This was the only location that had sufficient sample sizes and ranges of CPL to compare PCBs from hatchery and wild coho salmon. Again, we observed a relatively strong correlation of PCBs with CPL for wild fish (r^2=0.54, p=0.023), but not for fish of hatchery origin. In addition, PCBs in three of the seven Nisqually hatchery-origin samples were substantially higher (roughly two times greater) than any wild Nisqually sample. Essentially, this means that average PCB concentrations were higher in hatchery fish and hatchery-origin fish were responsible for much of the relatively high CPL-specific PCB concentrations observed for combined hatchery and wild coho salmon from the Nisqually River in Figure 3a.

To examine the effects of gender independent of location and hatchery or wild origin, we plotted PCB concentration versus CPL for wild fish from a single location, the Deschutes River. This location was the only one where we had collected sufficient numbers of composites of both sexes (11 males and 10 females; Table 2) across a relatively wide range of lipid values. Scatter plots (not shown for brevity) revealed no apparent disparity in the relationship of total PCBs and lipids between males and females. Thus, there was no evidence that gender of coho salmon affected the observed location-specific variation in PCB concentration.

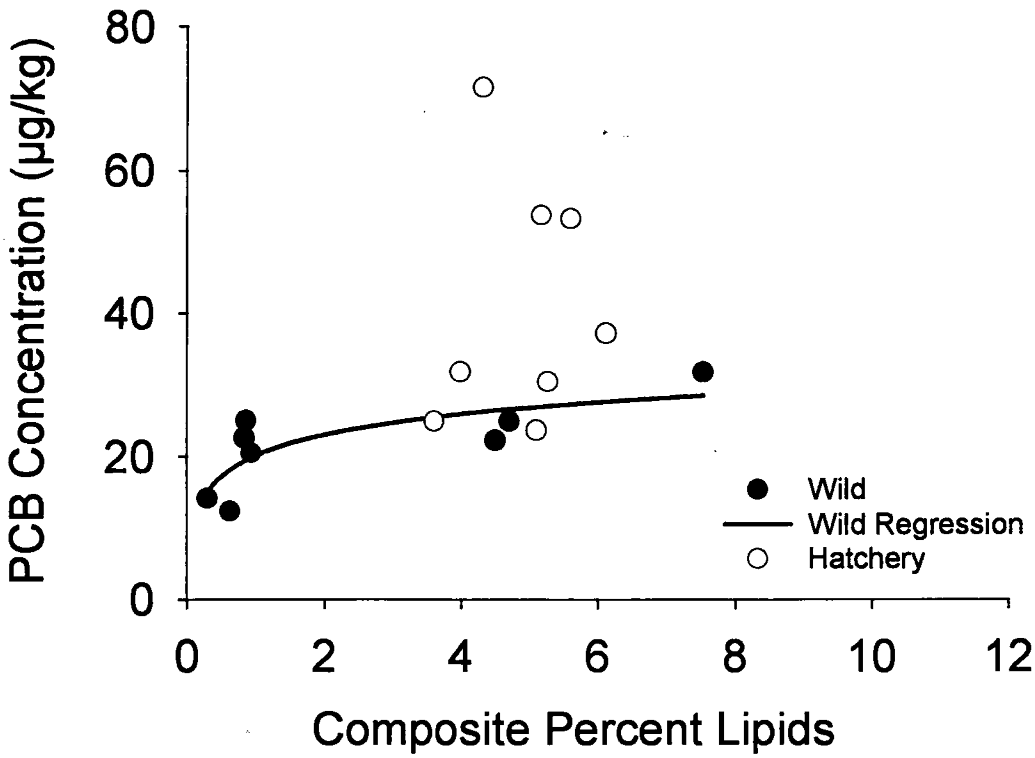

Figure 5. Relationship between total PCBs and tissue lipid content for wild coho salmon from the Nisqually River. Scatter plot of hatchery coho overlain for comparison. Linear regression analysis on log-linearized lipid data was used to fit line to wild coho data. The correlation for hatchery data was not significant ($p>0.05$).

Chinook Salmon

Evaluating the factors that affect PCB accumulation in chinook was more difficult because of their relatively complex life history. Most of the chinook salmon were three or four years old, but they ranged from two to five years old overall. The amount of time these fish spent in rivers, estuaries, and marine environments varied considerably. Most of the chinook salmon were ocean-type fish that went to sea in their first year of life, but some of the three- to five-year-olds were stream-types that went to sea in their second year. Chinook salmon were combined in composite-samples to create 44 stream-type, 93 ocean-type and 41 mixed-type life-history samples (Table 3). All but one of the stream-type fish were of hatchery origin; the origins of the ocean-type chinook were unknown because characteristics specific to their scale patterns preclude this type of determination.

Table 3. Number of composite tissue samples collected from adult chinook salmon from in-river and marine locations in Puget Sound Rivers, 1992–1995.

Location Type	Station	Stream Type Wild Origin	Stream Type Hatchery Origin	Ocean Type (unknown origins)	Mixed Fish Type (unknown origins)
In-river	Nooksack River	0	1	24	3
	Skagit River	1	9	10	9
	Duwamish River	0	11	16	6
	Nisqually River	0	3	16	1
	Deschutes River	0	14	10	10
Marine	Central Sound	0	2	8	8
	Southern Sound	0	3	9	4

Insufficient numbers of sample composites with unique combinations of origin, age, and life-history type prevented us from fully evaluating the effect that these factors might have on accumulation of PCBs in chinook salmon. Future sampling efforts will be designed to isolate factors by sampling individual fish or creating homogenous composites. Preliminary results for the present samples suggest that, for ocean-type chinook salmon, PCB concentration varied with fish age (data not shown) and only for four-year-old fish did PCB concentration increase with lipid content in the muscle tissue (Figure 6). PCB concentrations in stream-type fish (all ages and locations combined) were also not correlated with lipid content (data not shown).

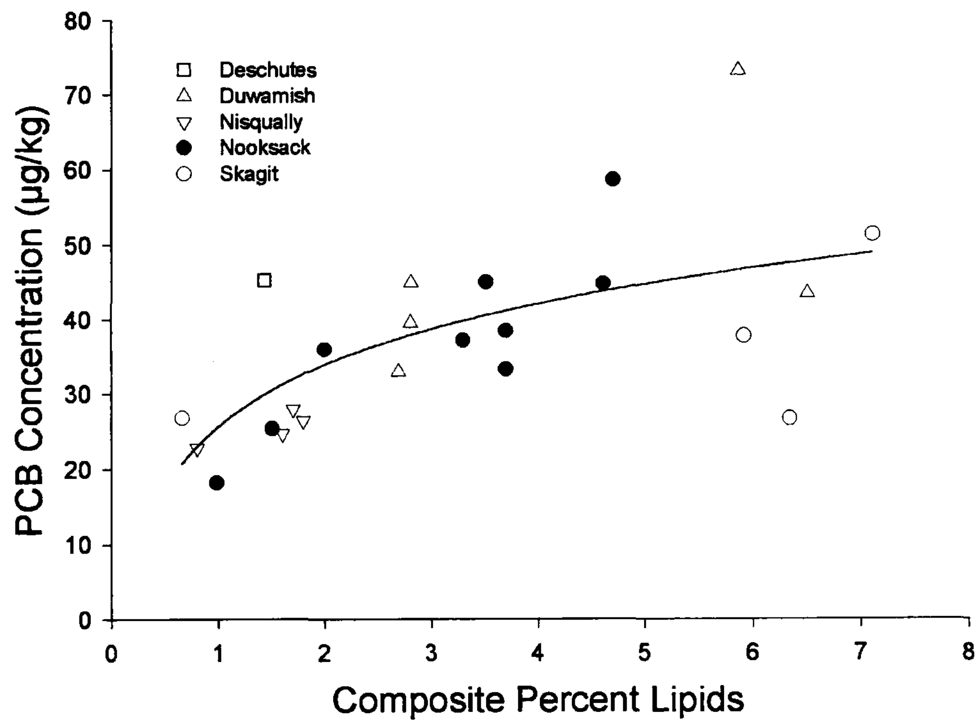

Figure 6. Relationship between total PCBs and tissue lipid content for four-year-old ocean-type chinook salmon from five in-river locations. Linear regression analysis with log-linearized lipid data was used to compute correlation coefficient for all locations combined.

Discussion

We investigated a number of factors as possible correlates with concentration of PCBs in muscle tissue of chinook and coho salmon from various marine and in-river locations in Puget Sound. We observed that chinook salmon had significantly higher PCB concentrations than coho salmon and within each species, PCB concentrations were higher in fish caught in marine areas than in-river areas (Figure 2, Table 1). For coho salmon, lipid content and sampling locations accounted for most of the observed variation in PCB concentrations (Figure 3). The location differences in PCB concentrations in these fish appears to be associated with a north-south location effect and the hatchery or wild origin of the fish (Figures 4 and 5). Male and female coho salmon accumulated PCBs similarly. Also fish age and year of migration to sea was not a factor affecting PCB accumulation in coho salmon because all of the fish were three-year-olds that went to sea in their second year of life. For chinook salmon, however, our preliminary review of the data suggests that the age of the fish may affect PCB accumulation. Average PCB concentrations in chinook salmon varied among fish ages with the highest concentrations occurring in three-year-old ocean-type fish and four-year-old stream-type fish. But, PCB concentration in muscle tissue increased with lipid content only for four-year-old fish that went to sea in their first year (ocean-type, see Figure 6).

Meaningful comparisons of PCB concentrations in tissues of chinook and coho salmon from different Puget Sound locations, and throughout time, can only be made with some understanding of their life history traits and how variation in these traits may affect exposure to and accumulation of PCBs in these species.

Because of their anadromous life-history, Puget Sound chinook and coho salmon occupy three distinct habitat types during their lifetimes, each of which may present different PCB exposure potential: (1) freshwater habitats, where eggs hatch and fry develop; and (2) Puget Sound, where smolts enter marine waters to feed and reside for some time during migration to (3) ocean habitats. Thus, inter- and intra-specific variation in movement patterns, and age at reproduction will affect the amount of time populations of chinook and coho salmon spend in different habitats and, subsequently, their potential PCB exposure.

The higher average PCB concentrations we observed in chinook than coho salmon may be the result of differences in: (1) the total time each species spends in fresh water, Puget Sound, and oceanic waters; (2) fish age; (3) diet; and (4) tissue lipid content. Chinook and coho salmon differ in their migration patterns and habitat use. Typically, Puget Sound coho migrate from fresh water to the sea in their second year, followed by a relatively brief estuarine (river-mouth) residence and about one to two years in Puget Sound, the southwest coast of Vancouver Island or the northern Pacific coast of Washington. They return as three-year-olds to spawn in their natal streams. Unlike coho salmon, juvenile chinook salmon may go to sea in their first or second year (ocean- or stream-type juveniles) and may return to spawn as two-, three-, four-, and five-year-olds. Stream-type juvenile chinook salmon reside in fresh water for a full year prior to their seaward migration in their second year, make limited use of estuaries, and tend to migrate to the North Pacific Ocean. Ocean-type juvenile chinook (the predominant form in Puget Sound rivers) migrate to sea in their first year of life (at a smaller size than the stream-type smolts), spend more time in estuaries, and have a more coastal distribution during their period at sea (Healy 1991). Because of these differences in their ages and migration patterns, chinook salmon in Puget Sound generally spend more time in marine waters than do coho salmon.

We suggest that chinook and coho salmon accumulate most of their PCB body-burden in the marine waters of Puget Sound and the ocean, and because chinook salmon live longer and stay at sea longer than coho salmon they accumulate higher PCB concentrations in their muscle tissues. Combining our data with those of Varanasi et al. (1993), we estimated that the likely contribution of PCBs to adult salmon body burdens attributable to movement though freshwater and estuarine habitats as young was negligible. Varanasi et al. (1993) demonstrated that chinook salmon smolts migrating out to Puget Sound through one of its most polluted estuaries (the Duwamish Waterway) were exposed to PCBs at a

maximum concentration of approximately 260 µg/kg in 1989. Based on mean size of those smolts, we estimated their body burdens at 1.4 g PCB per smolt. The chinook salmon adults we sampled in 1992 and 1993 were probably either of the same cohort, or within one year of the same cohort, of those sampled by Varanasi et al. (1993) in 1989. Assuming that 55% of the adult body mass was muscle tissue (we used estimates for sockeye salmon, *Oncorhynchus nerka* from Gilhousen (1980) and using our average PCB concentration and weight of chinook salmon returning to the Duwamish River, we estimated a total body burden of 130 g PCB per adult. Hence, the smolt body burden we estimated from Varanasi et. al. (1993), (1.4 µg/smolt) accounted for only 1.1% of the total PCB body burden estimated for adult chinook salmon. In other words, according to these computations and assumptions, about 99% of PCBs in adult chinook salmon returning to spawn in the Duwamish/Green River watershed were accumulated by the fish in the marine waters of Puget Sound or the Pacific Ocean.

Diet differences between chinook and coho salmon in marine waters may further account for some of the observed differences in PCB concentrations between these fish. Both species consume a wide variety of invertebrate (e.g., euphausiids, hyperiid amphipods, crab larvae) and fish (e.g., Pacific herring and Pacific sand lance) prey. However, adult chinook salmon tend to consume a greater percentage of fish than coho salmon (Fresh et al. 1981; Peterson et al. 1982; Beacham 1986; Higgs et al. 1995), resulting in a longer food chain for chinook salmon. The more piscivorous nature of adult chinook salmon may increase their exposure to PCBs because of biomagnification of the contaminants in the food web. Bentzen et al. (1996) observed that PCB and DDT concentrations in lake trout were proportional to tissue lipid concentrations (as we have seen) but the magnitude of the concentrations varied, due to either food chain length or differences in contaminant loading. Other researchers have demonstrated the importance of trophic status in accumulation of persistent pollutants like PCBs in freshwater salmonids and marine fishes (Young et al. 1980; Borgmann and Whittle 1992; Hammar et al. 1993; Madenjian et al. 1993; Madenjian et al. 1994; Davenport 1995; Kidwell et al. 1995; Stow 1995; Kidd et al. 1998).

Although, tissue lipid levels were correlated with PCB concentration for both chinook and coho salmon, the range of lipid levels observed between species were similar (grand means of 3.4% and 3.1%), suggesting that this factor did not contribute substantially to the species-specific PCB differences we observed.

Variability in any number of the above factors may account for the range of PCB concentrations we observed between these species, and between the in-river and marine fish. It is impractical to account for all such factors given sampling schemes typical of monitoring programs. However, we have observed that for coho salmon, location of capture, tissue lipid concentration, and possibly hatchery/wild origin are important factors in interpreting PCB concentration data.

PCBs were proportional to lipid levels in coho salmon from four of five in-river Puget Sound locations; however, the magnitude of lipid-specific PCB concentration depended on location. Coho salmon (hatchery and wild fish combined) from the Nisqually and Deschutes rivers had higher lipid-specific PCB concentrations than coho from the Nooksack and Skagit rivers (Figure 3a). Many physical or environmental differences distinguish these four watersheds, however. One of the most obvious is their north-to-south distribution. Coho salmon from the southern Puget Sound rivers (Deschutes and Nisqually) had greater lipid-specific PCB concentrations than from the northern rivers (Skagit and Nooksack). In addition, marine-caught coho salmon from southern Puget Sound had higher PCB concentrations than those from central (that is, more northern) Puget Sound areas (Figure 3b).

These patterns may be related to intraspecific variability in migration patterns or the total time coho salmon spend in Puget Sound versus oceanic waters. Puget Sound habitats likely present a greater potential exposure of PCBs to salmon than oceanic habitats, based on the presence of urban and industrialized areas and known contamination hot spots in Puget Sound. If so, then salmon that spend more time in Puget Sound than oceanic waters may experience greater exposure to PCBs. Salmon originating from southern Puget Sound watersheds must travel a greater distance in Puget Sound before they reach oceanic waters during their out-migration and during their return spawning migration to natal

watersheds. In addition, it is likely that prey consumed in central and southern Puget Sound would have higher PCB concentrations due to the larger number of locations in central and southern Puget Sound with PCB-contaminated sediments (Puget Sound Water Quality Action Team 1998). Salmon originating from northern watersheds have a shorter migration to oceanic waters, and they do not have to pass through polluted areas as do the salmon from more southern watersheds.

The total time a salmon spends in Puget Sound, or, its "residency," is unknown and probably highly variable (see Buckley 1969; Buckley and Haw 1978). Some outmigrating wild salmon may naturally remain resident in Puget Sound year-round (termed "resident salmon" by anglers). The population of wild resident salmon is thought to be naturally low. Fishery managers have, since the 1970s, attempted to increase populations of resident Pacific salmon by delaying the release of juveniles for a period ranging from several weeks to over a year. This practice, it is thought, tends to inhibit the out-migration of salmon, providing a year-round fishery for Puget Sound anglers (Appleby and Doty 1995).

Although the overall correlation of PCBs to lipids was fairly strong for coho salmon (Figures 3a and 3b), a number of composite samples did not fit the patterns well (Figures 3b, 4b, and 5). These "outlying" composites were composed entirely of hatchery-origin fish or fish of unknown origin. It is possible that these hatchery-origin samples were delayed-release fish that were "resident" in Puget Sound and thus experienced a greater exposure to PCB contamination. We were unable to determine with confidence whether any of our sampled salmon had been resident in Puget Sound. However, the life history of a significant portion of hatchery-origin coho (more than four million per year from 1983 to 1993) and chinook salmon (one million or more per year since 1974) have been manipulated to encourage residency (Appleby and Doty 1995).

The Duwamish River is the most polluted of the five in-river areas we sampled, yet coho salmon from relatively unpolluted locations had both higher (Deschutes and Nisqually rivers) and lower (Skagit and Nooksack rivers) concentrations of PCBs. The PCB concentrations of coho salmon from the Duwamish were intermediate between those from the southern and northern locations, supporting the geographic trend noticed in the lipid-specific data. The lack of a correlation between lipids and PCB concentration in muscle tissue for the Duwamish fish may results from the collection of hatchery fish at this location; four were hatchery-origin, two were wild, and nine were of mixed hatchery and wild origin.

Health of Pacific Salmon in Puget Sound

The effects of PCB accumulation on the health of chinook and coho salmon from Puget Sound are unknown. Salmon typically metabolize lipids as a source of energy during their spawning migrations, so fish closer to spawning generally have lower levels of lipid in their muscle tissues (see review in Brett 1995) and (consequently) lower PCB concentrations. However, accumulated PCBs may be transferred to the eggs and the resulting concentrations may be high enough to reduce reproductive success in individual fish. A study of chinook salmon in Lake Michigan (Ankley et al. 1991) showed that hatchery success decreased with increased PCB concentration in eggs. Chinook and coho salmon from Lake Michigan (Stow et al. 1994) had about 10 times the PCB concentrations in their muscle tissue that we observed in Puget Sound salmon. It is unknown whether PCB concentrations in Puget Sound salmon are transferred to eggs in high enough concentrations to affect hatching success and survival of fry.

Several studies have documented that juvenile salmonids in highly contaminated areas in Puget Sound (Duwamish River and Hylebos Waterway) are exposed to higher concentrations of organic contaminants, including PCBs, than fish from hatcheries and reference areas (McCain et al. 1990; Varanasi et al. 1993; Stein et al. 1995; Collier et al. in press). Furthermore, chinook salmon from the Duwamish estuary showed suppression of immune function, increased mortality after disease challenge, and impaired growth (Arkoosh et al. 1991; Varanasi et al. 1993). A recent laboratory study (Arkoosh et al. 1994) showed that exposure to chlorinated hydrocarbons and PAHs may impair immunocompetence of juvenile chinook salmon. Although exposure to contaminants is correlated with reduced growth rates and short-term survival, the effects on long-term marine survival and abundance of salmon populations are unknown.

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Categorization of Suspended Particulate Matter (SPM) in Whidbey Basin

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Introduction

Suspended particulate matter (SPM) is a major factor in regulating the dispersion of pollutants and other chemicals in marine waters. The movement of SPM can indicate where pollutants and resuspended materials are being transported and deposited. SPM is controlled by biological, chemical, physical, and geological processes (Baker, 1984; Owens et al., 1997). Examining SPM for organic and inorganic materials as well as vertical distribution will provide a better understanding of these processes.

Our study area was at Department of Ecology (DOE) site PSS019, landward of Gedney Island in the southeastern portion of the Whidbey Basin (48° 1' N, 123° 18' W) (Figure 1).

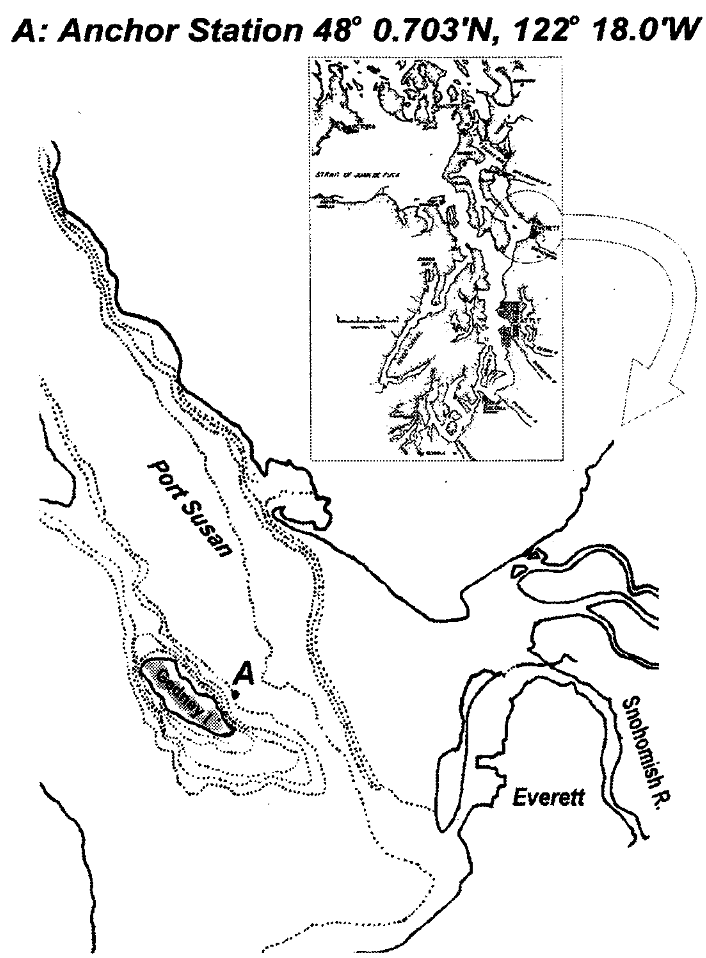


Figure 1. A map of Puget Sound with an expanded view of the study site in the Whidbey Basin. Note that there are three major rivers (Stillaguamish, Skagit, and Snohomish) emptying into this basin. A: Anchor station at 48_ 0.703' N, 122_ 18.0' W.

The site is near Everett, WA and has received little attention pertaining to SPM and other oceanographic details. SPM at this DOE site has never been examined and may prove to give valuable insight to sediment transport in the Whidbey Basin. This area is also very interesting because ~70% of the freshwater input to the Puget Sound flows through this area from the three large rivers (Skagit, Snohomish, and Stillaguamish Rivers).

Methods

From 16–18 April, 1997, water samples were collected every three hours with 12 5-liter Niskin bottles at varying depths. Sub-samples were transferred into one-liter bottles and filtered through pre-weighed 0.7-µm glass fiber filters (Whatmann GF/F). Then filters were rinsed with distilled water to remove salts. They were also examined with a dissecting scope for a qualitative description of the particulate matter. Filters were placed in prelabled Petri dishes and dried until their weight was constant. Finally, filters were moved to an oven set at 450°C for 12 hr to burn off all volatile material.

Temperature, conductivity, pressure, and percent transmission were measured electronically using a Sea-Cat CTD. These measurements were taken continuously through the water column as per the method outlined by Crone (1997). Percent transmission data was converted to absorbance in order to show a positive trend between absorbance and SPM concentrations.

Transmission data has been used in other studies to show correlation between beam transmission and SPM concentration (Baker, 1984; Wells and Kim, 1991).

Results

SPM had a maximum concentration at 0 m (approximately 4.8 mg/L), which decreased to a minimum between 30 to 60 m (Figure 2).

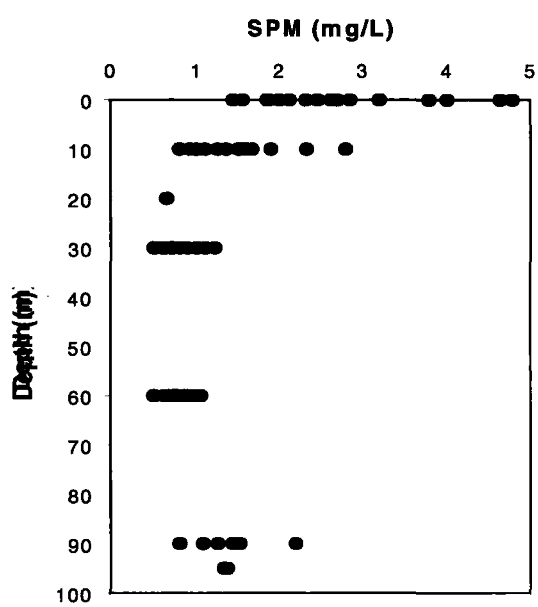


Figure 2. SPM concentration vs. depth data from discreet samples taken during study period.

Particulate organic matter (POM) followed a similar trend. However, inorganic particulate matter (IPM) had a maximum concentration at the surface decreasing to a minimum at 30 m (approximately 0.1 mg/L) and increasing at 90 m (Figure 3).

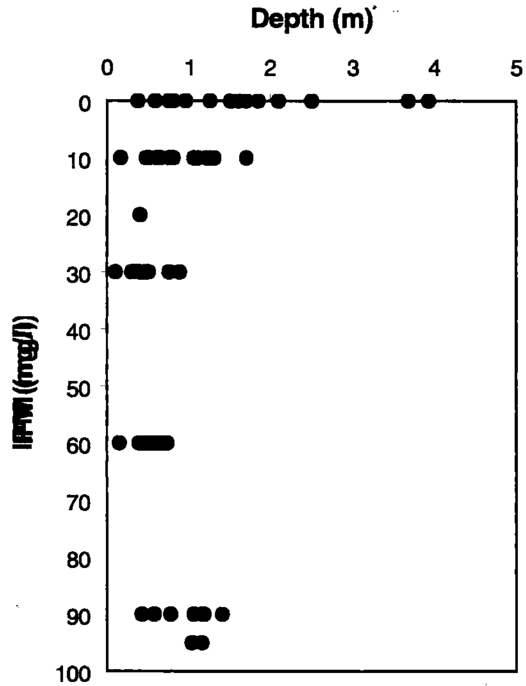


Figure 3. IPM vs. depth profile from discreet bottle samples.

POM and IPM values are in agreement with the results of the visual analysis we made of the samples prior to drying. We found phytoplankton and fecal matter to be greatest at the surface and lowest at 90 m. In the surface waters IPM was present as mud and opal from biological organisms. In 90-m samples, the IPM was observed as silt.

At surface and bottom depths the absorbance data had maximum values which correspond to SPM maximum values. When SPM and absorbance data from all casts were taken into account, no direct relationship between SPM and absorbance was found. However, in single casts a correlation was found between SPM and absorbance (Figure 4).

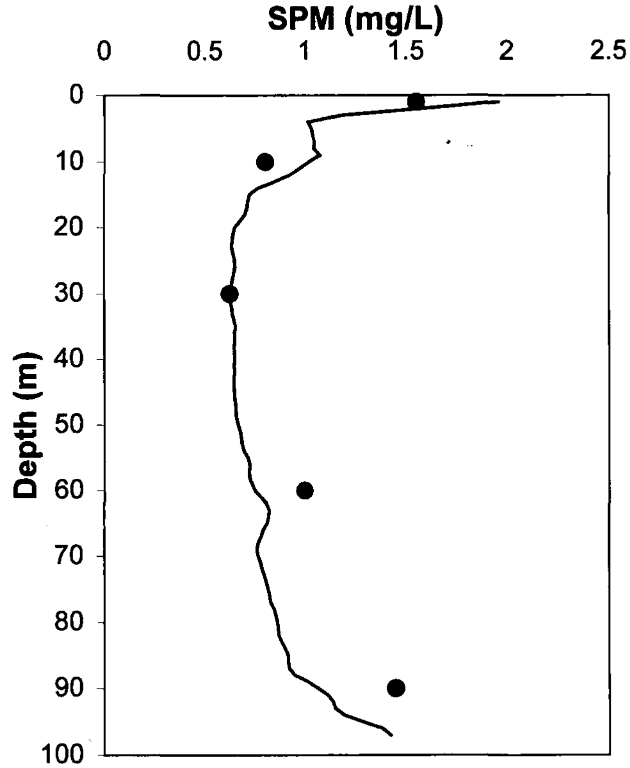
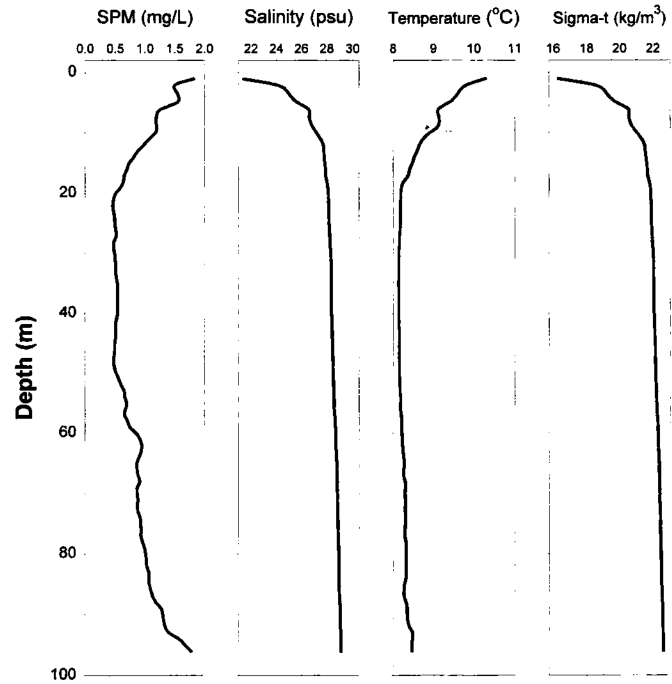


Figure 4. SPM vs. depth profile after correlating absorbance with discreet samples. This is cast 17 of 19, with r^2 of 0.65.

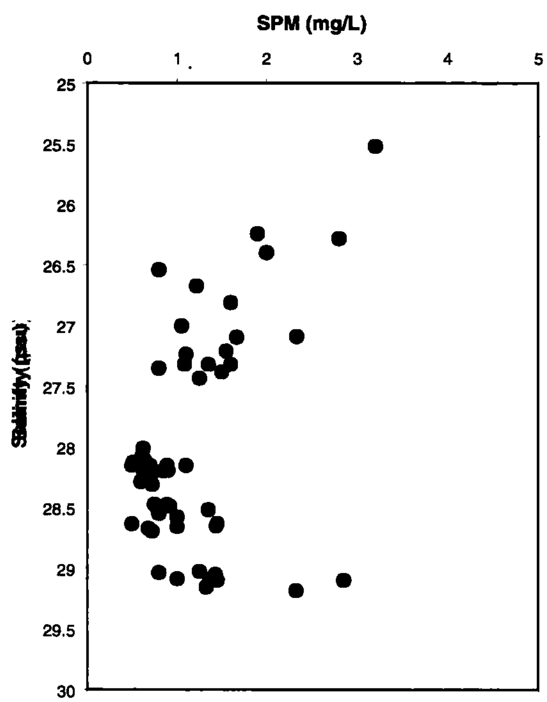
The relationship of in-cast SPM to absorbance allowed us to calculate SPM trends at continuous depths by looking at absorbance in each single cast.

Discussion

The temperature, salinity, and density vs. depth plots show three distinct water types at the study site (Figures 5a,b). The increase in density and salinity at ~10 m corresponds to the change from river influenced water to intermediate Puget Sound waters. The salty, dense, warmer bottom-water mass may be a result of intruding seawater. Finally, the mid-depth layer has increasing salinity and density and decreasing temperature with depth due to mixing of the top and bottom layers.



(a)



(b)

Figure 5(a). SPM, salinity, potential temperature, and density vs. depth for the study site. Cast 17 of 19. (b) Salinity vs. SPM. This graph shows the intruding salty bottom water as an increase in SPM with salinity after 28.5 psu.

Our findings of high levels of SPM in the top (0–10 m) and bottom (90 m) of the water column agree with other research done in the main basin of Puget Sound (Baker, 1984). Baker (1984) found high levels of light attenuation in the upper and lower layers of the water column, which corresponds to our measured high levels of absorbance. Baker also comments on a bottom nepheloid layer (BNL) which is present in the main basin of the Puget Sound (1984). Our high particle levels in the bottom waters extend this BNL into the Whidbey Basin. The BNL is the major transport mechanism of bottom sediment of the Puget Sound (Baker, 1984). Our deep water measurements were all taken at low bottom water motion (slack or near-slack tides) and were all approximately 10 m from the bottom, yet show the BNL, suggesting that it is present throughout tidal cycles.

The observed high concentrations of SPM in the upper layer may be due to several processes. Detritus and some phytoplankton and zooplankton may have a difficult time penetrating the high-density barrier between the top and mid layers. Also there is an area of no net motion between the outgoing river runoff and the incoming tidal flow (Barnes and Ebbesmeyer, 1978). The interface between the two oppositely flowing water layers may also be an area of high turbidity. The zone of high turbidity along with the strong pycnocline may act as a strong SPM capture area for low-density material. River runoff carrying sediment from the Stillaguamish, Snohomish, and Skagit Rivers emptying into the Whidbey Basin, along with opaline phytoplankton material, contribute to high IPM surface concentrations.

The percent POM and POM concentration vs. depth (Figure 6) showed interesting results. When POM concentration vs. depth was examined, a trend of relatively high concentration in the upper layer with decreasing concentrations down to the BNL can be seen. However, the trend in the percent POM indicates organically enriched SPM in the mid-depth layer.

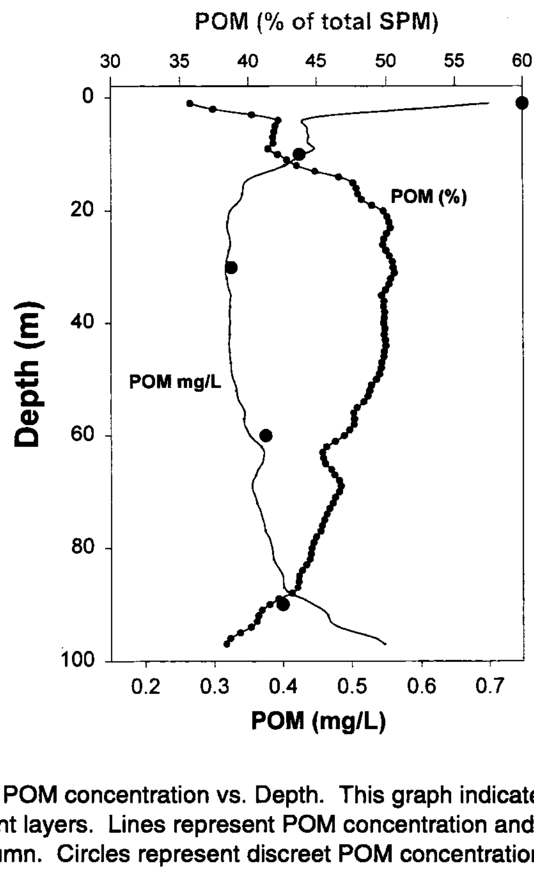


Figure 6. %POM and POM concentration vs. Depth. This graph indicates the composition of the SPM in the different layers. Lines represent POM concentration and %POM continuously through the water column. Circles represent discreet POM concentration data taken from bottles.

At the BNL, the concentrations of POM increase while percent POM decrease. The relatively low density POM has a longer residence time in the slower moving mid-depth layer while high-density IPM settle through the mid-depth layer to the bottom where it may be resuspended by the BNL.

In conclusion, SPM has three distinct layers through the water column in the Whidbey Basin. These layers have approximately the same profile and the same concentrations of that in the main basin. The surface layer (0–10 m) has a high concentration of SPM dominated by IPM. This surface layer is flowing southward and carries river debris and biological organisms out of the study area. The SPM concentrations decrease in the mid-layer where there is a high percentage of low density POM. This organically rich mid-depth layer has a zero net motion and has large residence times in this basin. The bottom layer contains a BNL, which has a high SPM concentration dominated by IPM. The BNL is a major factor in the movements of bottom sediments, and is present at all times over much of the Puget Sound (Baker, 1984). Particles are resuspended from the bottom and carried by the circulation of bottom water (Baker, 1984). Unfortunately, we were unable to obtain the direction of bottom water motion in the Whidbey Basin which would provide the direction of bottom sediment transport.

Acknowledgments

Our thanks go out to Rick Keil and the Aquatic Organic Geochemistry group at the University of Washington for much needed guidance and support. Also we thank the Physical Oceanography 201 students (1997) for their cooperation and information sharing. Without Jan Newton and the Department of Ecology we wouldn't have had such an exciting place to study. Finally, thanks go to Ray McQuin and the entire *R/V Barnes* crew for hosting a group of undergraduates for two days.

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Persistent Pollutants and Factors Affecting Their Accumulation in Rockfishes (*Sebastes* spp.) from Puget Sound, Washington

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Introduction

As a participant in the Puget Sound Ambient Monitoring Program (PSAMP), the Washington Department of Fish and Wildlife (WDFW) has evaluated contaminant levels in a number of marine and anadromous fish species from 1989 to the present. Among its targets are quillback rockfish (*Sebastes maliger*) and brown rockfish (*S. auriculatus*). These rockfish species are demersal, long-lived[i] carnivores that typically associate closely with complex, high-relief substrates such as rocky reefs (Matthews 1990). Because of their site-fidelity, trophic status, and long life-expectancy, these rockfishes are expected to have a high probability of accumulating persistent pollutants such as mercury (Hg), polychlorinated biphenyls (PCBs), and organochlorine pesticides if present in their environment.

Previous WDFW work (West and O'Neill 1995) identified PCBs and Hg (of 99 organic and inorganic toxic contaminants tested) as the most commonly detected contaminants observed in high enough concentrations to cause concern in rockfish from Puget Sound[ii]. That study reported results from 1989—1993 for rockfish muscle tissue composites, where each sample consisted of tissue mixed together from five fish. The compositing procedure is generally used to lower statistical variability in contaminant concentrations to increase the power of detecting differences between locations. However, compositing also dampens the full range of concentrations otherwise observable from individuals. This problem is especially acute for long-lived species like rockfish, where composites may be comprised of fish with a wide range of ages.

In order to obtain a more accurate estimate of the range of individual concentrations of PCBs and Hg in rockfish, as well as to identify more accurately the relationship of these contaminants with factors such as fish age, WDFW initiated analyses of individual rockfish in 1995. The present paper presents results from sampling individual quillback and brown rockfish from 1995 through 1997 for mercury, and 1995–1996 for PCBs.

Methods

Quillback and brown rockfish were sampled using bottom-trawls and hook-and-line from six locations in the Puget Sound (Figure 1). Rockfish from Double Bluff, San Juan Islands and Blakely Rocks were taken with hook-and-line in October though November, 1995. Rockfish from Sinclair Inlet and Foulweather bluff were taken with bottom trawls in April, 1995 and May, 1997, respectively. Rockfish from Elliott Bay were taken using hook-and-line and bottom trawls in October through November, 1995, and April through May, 1996 and 1997. Sample sizes ranged from eight (for Sinclair Inlet) to 42 (for Elliott Bay); all samples except five brown rockfish from Sinclair Inlet were quillback rockfish. Upon landing, fish were labeled with numbered external tags, measured for total length (mm), wrapped in aluminum foil, sealed individually in plastic bags, and placed on ice for transport to the laboratory. Sagittal otoliths were removed for estimating fish ages; presumed annual increments were counted from broken-and-burned surfaces. In the laboratory, up to 250 g of lateral skeletal muscle tissue was excised from skinned fish within 10 days of collection, and immediately frozen for later chemical analysis.

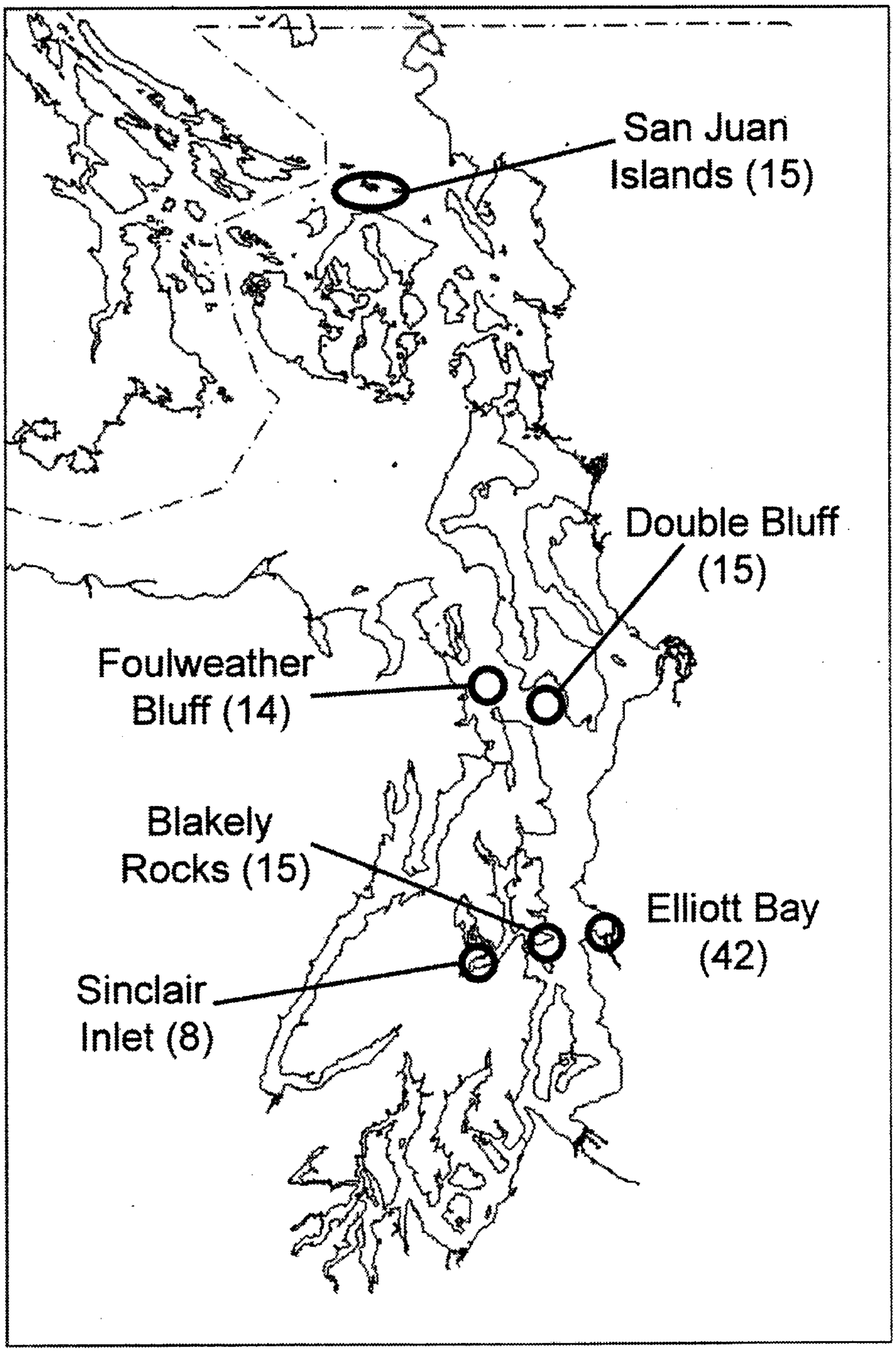

Figure 1. Location of sampling locations for quillback and brown rockfish in Puget Sound. Samples were taken from San Juan Islands, Double Bluff, and Blakely Rocks using hook-and-line in the fall of 1995; Foulweather Bluff and Sinclair Inlet were sampled using bottom trawls in the fall of 1997 and spring of 1996, respectively. Elliott Bay was sampled using hook-and-line and bottom trawls in the fall of 1995 and the spring of 1996 and 1997. Numbers in parentheses indicate sample sizes.

Total mercury concentration of individual muscle tissue samples was determined by cold-vapor atomic absorption after digestion with nitric/sulfuric (Puget Sound Estuary Program 1996a). PCBs were analyzed using gas-chromatography-electron capture detection with a dual megabore (Puget Sound

Estuary Program 1996b). Tissue lipid concentration was estimated gravimetrically from samples where lipids were removed using acetone/methylene chloride extraction.

Least squares model I linear regression analysis was used to model the relationship between contaminant concentration and fish age. Stepwise forward linear regression variable selection with a confidence level of 95% was used to identify statistically significant factors. Location effects were isolated in regression analyses using dummy variables (Kleinbaum and Kupper 1978).

Table 1. Summary of fish age, length, tissue lipids, mercury and PCB data for quillback[a] and brown rockfish from six locations in Puget Sound, Washington.

Location		Fish Age (yrs)	Total Length (mm)	Tissue Lipids (%)	Mercury (mg/kg)	Total PCBs[b] (µg/kg)
	Mean	13.9	318	2.8	0.24	43.2
Blakely	Std. Dev.	5.2	20	4.0	0.11	34.0
Rocks	Min.	8	292	0.1	0.08	11.4
	Max.	28	373	15.8	0.46	138.8
	n	15	15	14	15	15
	Mean	12.6	319	0.4	0.22	5.1
Double	Std. Dev.	2.8	15	0.6	0.08	3.0
Bluff	Min.	7	297	0.1	0.10	4.0
	Max.	17	347	2.6	0.38	14.1
	n	15	15	15	15	15
	Mean	13.9	308	1.1	0.38	122.4
Elliott	Std. Dev.	4.6	33	1.7	0.16	71.5
Bay	Min.	5	220	0.1	0.08	54.4
	Max.	23	381	6.0	0.74	356.0
	n	42	39	15	39	19
	Mean	7.5	321	---	0.29	---
Foulweather	Std. Dev.	3.8	48	---	0.16	---
Bluff	Min.	3	233	---	0.14	---
	Max.	18	393	---	0.75	---
	n	14	14	---	14	---
	Mean	16.0	363	0.5	0.26	3.9
San	Std. Dev.	13.4	42	0.2	0.19	0.5
Juan	Min.	6	292	0.2	0.08	2.0
Islands	Max.	60	416	1.1	0.81	4.0
	n	15	15	14	15	15
	Mean	24.3	372	0.4	0.84	268.3
Sinclair	Std. Dev.	6.8	25	0.2	0.23	201.4
Inlet	Min.	14	340	0.1	0.51	84.7
	Max.	34	418	0.7	1.09	613.0
	n	8	8	8	8	8

[a] all samples were quillback rockfish except five brown rockfish from Sinclair Inlet
[b] sum of Aroclors 1254 and 1260

Results

Mercury

Concentrations of total mercury from individual fish ranged from 0.08 mg/kg in samples from Blakely Rocks, Double Bluff, Elliott Bay and San Juan Islands to 1.09 mg/kg from Sinclair Inlet Table 1). Mean mercury concentration for four non-urban locations (Blakely Rocks, San Juan Islands, Foulweather Bluff, and Double Bluff) ranged from 0.22 to 0.29 mg/kg; mean mercury concentration from the two urban locations was 0.38 mg/kg (Elliott Bay) and 0.84 mg/kg (Sinclair Inlet). Mercury concentration was moderately to strongly correlated with fish age for all locations (linear regression analysis, r^2 ranging from 0.48 to 0.82; Figure 2). Mean ages of rockfish varied widely among locations—from 7.4 years at Foulweather Bluff to 24.3 years from Sinclair Inlet. Thus, comparisons of mercury concentration among locations required an accounting of these location-specific age differences.

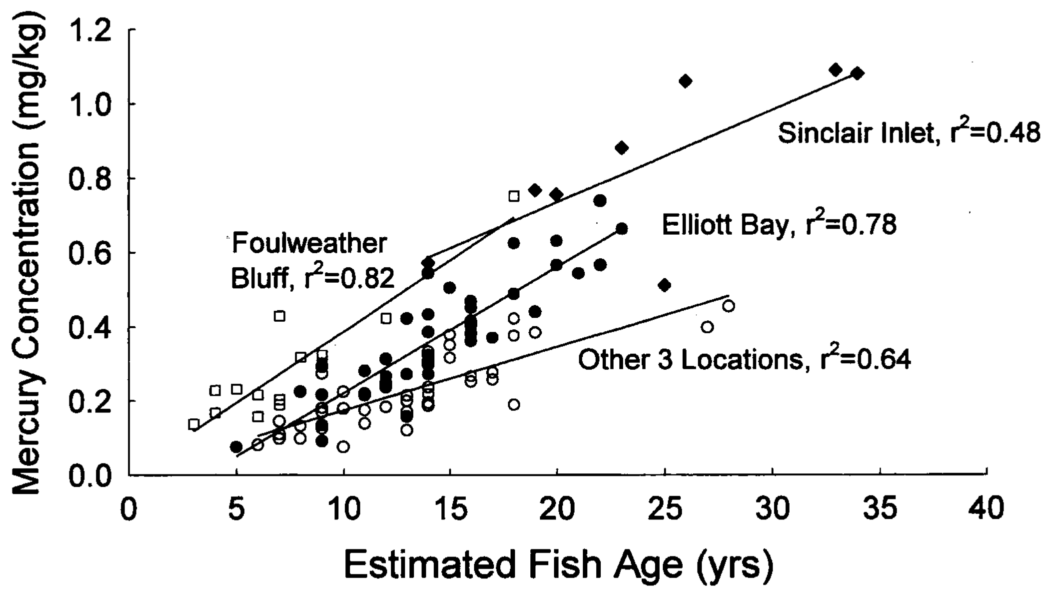

Figure 2. Accumulation of mercury in muscle tissue from quillback and brown rockfish sampled from Sinclair Inlet (diamonds), Foulweather Bluff (open squares), Elliott Bay (filled circles), and three locations (San Juan Islands, Double Bluff, and Blakely Rocks) grouped together (open circles). Lines were fitted using least squares model I linear regression analysis; $p<0.05$ for all regressions.

Comparing the relationships of mercury concentration with fish age graphically (Figure 2) allows an inspection and comparison of mercury concentration-at-age for each location. Mercury increased with age in rockfish from all locations; accumulation patterns from San Juan Islands, Double Bluff and Blakely Rocks were similar enough[iii] to pool their data into a single linear regression (Figure 2). Sinclair Inlet, Elliott Bay, and Foulweather Bluff all had higher age-specific mercury concentration than the other three locations.We observed no differences in accumulation based on gender or tissue lipid levels.

Mercury in all eight samples of quillback and brown rockfish from Sinclair Inlet exceeded 0.5 mg/kg, and three exceeded 1.0 mg/kg; however, these were all relatively old fish, with ages ranging from 14 to 34 years. Rockfish from Foulweather Bluff appeared to have a similar pattern of accumulation as fish from Sinclair Inlet, but because there was little overlap in ages between the two locations, a valid comparison was not possible. Rockfish from Foulweather Bluff were all relatively young; their mean age was 7.5 years, compared to a range of means from 12.6 to 24.3 years for all the other locations. This resulted in a moderate mean mercury concentration for the location (0.29 mg/kg; Table 1). However,

for their respective age ranges, rockfish from Foulweather Bluff and Sinclair Inlet had the highest age-specific mercury concentrations.

Age-specific mercury concentration for Elliott Bay was intermediate, clearly higher than for the San Juan Islands/Double Bluff/Blakely Rocks group, and lower than for Sinclair Inlet or Foulweather Bluff. The sample size for Elliott Bay was relatively large (39 individuals) which probably resulted in a more accurate description of the mercury concentration:age relationship than the other locations, however the oldest fish sampled from that location was only 23 years of age.

PCBs

Polychlorinated biphenyls (PCBs), estimated as the sum of Aroclors 1254 and 1260, were consistently detected in three of five locations (Table 1). Average PCB concentrations were 43.2, 122.4, and 268.3 µg/kg for Blakely Rocks, Elliott Bay, and Sinclair Inlet, respectively; Maximum PCB concentrations for these locations were 138.8, 356.0, and 613.0 µg/kg. PCBs were never detected in rockfish from San Juan Islands, and were detected (near the limit of detection) in only two of 15 samples in rockfish from Double Bluff.

We observed significant correlations between fish age and PCB concentration only in male rockfish from the two urban locations (Figures 3a and 3b). However, the regression for Sinclair Inlet was based on only five samples, and the Elliott Bay relationship appears to have been defined primarily by the two oldest samples, aged 20 and 22 years. Confidence in the validity of these correlations would be increased with more samples, especially in the range of ages greater than 20 years. PCBs did not accumulate in males from Blakely Rocks.

However, PCB concentrations in all males were low (<139 µg/kg) and the range of rockfish ages from that location was relatively low (eight to 18 years; Figure 3c). We observed no significant correlation ($p>0.05$) between age and PCB concentration in female rockfish from any location (Figures 3a-c). In fact, PCB concentration seemed to decline with increasing age in female rockfish from Blakely Rocks (Figure 3c), however this weak correlation ($r^2=0.24$) was not significant ($p=0.12$).

Not shown is any analysis of PCBs and tissue lipid content. We inspected scattergrams for PCB concentration versus tissue-lipid content for each location-gender combination and observed no identifiable patterns.

Discussion

Perhaps the most striking result we observed in this study is the strong, consistent pattern of accumulation of mercury in rockfish from all locations, with no effects attributable to gender or tissue-lipid levels. These accumulation patterns not only illustrated the relatively high mercury concentration in rockfish from contaminated areas that one might expect, but also showed that mercury accumulated in rockfish from uncontaminated areas. This presumed "natural" accumulation of normal or background mercury has been recognized in other marine organisms (Barber et al. 1972; Bernhard and Renzoni 1977; Barber 1984; Francesconi and Lenanton 1992; Monteiro et al. 1996; Phillips et al. 1997). Surprisingly however, we observed the greatest age-specific mercury concentration from Foulweather Bluff, a location that was selected as an uncontaminated reference area. Possible explanations for this are explored below.

In addition to age, strong location-specific factors other than gender and tissue lipid levels influenced the concentration of mercury in quillback and brown rockfish. The simplest explanation for these differences is related to variation in the source of mercury, where the concentration of mercury in the fish's tissue reflects regional levels of mercury. Strong associations of mercury concentration in sediments with resident organisms have been reported for a number of substrate-associated marine organisms world-wide (Kiørboe et al. 1983; Mikac and Picer 1985; Clark and Topping 1989; Leah et al. 1991; Palmer and Presley 1993; Collings et al. 1996; Herut et al. 1996). This association has also been observed in English sole from Puget Sound (Puget Sound Water Quality Action Team 1998).

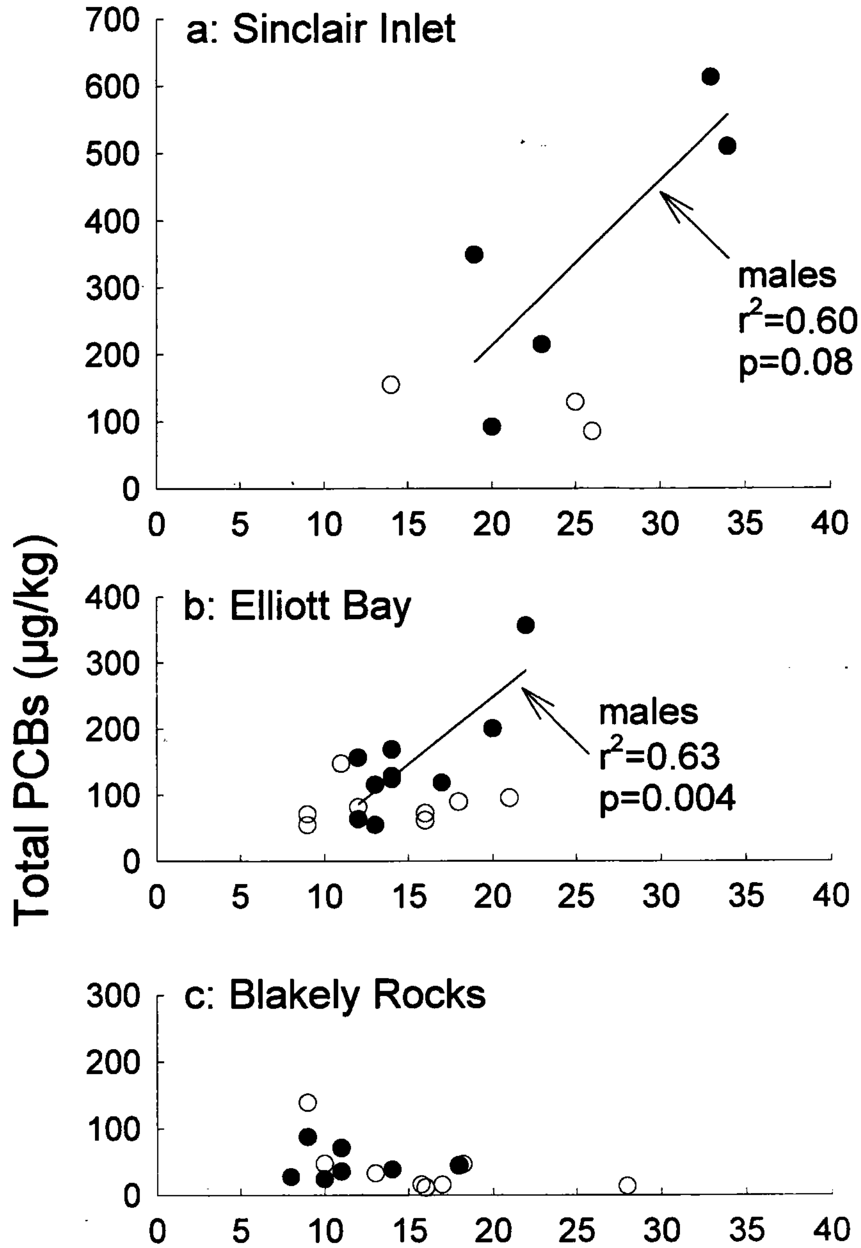

Figure 3. Concentration of PCBs and fish age for male (filled circles) and female (open circles) quillback and brown rockfish from three Puget Sound locations. Lines were fitted using least squares model I linear regression analysis; p=0.08 and 0.004 for Sinclair Inlet and Elliott Bay regressions.

For rockfish in Puget Sound, PSAMP sediment chemistry data have shown that Sinclair Inlet and one location in Elliott Bay were contaminated with mercury (Puget Sound Water Quality Authority 1995), supporting the sediment-to-fish link. However, sediment samples taken in the 1970s from the Foulweather Bluff area had some of the lowest levels of mercury in the Puget Sound (Bothner 1973), some 30 to 50 times lower than Sinclair Inlet and Elliott Bay at that time. This suggests that some factor other than sediment contamination has caused a high concentration mercury in rockfish from Foulweather Bluff.

Consumption of contaminated prey, rather than absorption from the water, probably represents the primary pathway of mercury in marine fishes (Francesconi and Lenanton 1992), and the position a species occupies in the food web exerts a great influence on the level to which it biomagnifies persistent pollutants such as mercury (Young et al. 1980; Borgmann and Whittle 1992; Francesconi and Lenanton 1992; Hammar et al. 1993; Madenjian et al. 1993; Cabana et al. 1994; Madenjian et al. 1994; Davenport 1995; Kidwell et al. 1995; Stow 1995). These studies have demonstrated or inferred the importance of trophic level on the degree to which a species is exposed to persistent pollutants like mercury and PCBs; the result is that carnivorous organisms tend to accumulate these contaminants in greater concentrations than organisms lower in the food chain

Because of the great diversity of prey consumed by rockfish, it is difficult to connect rockfish directly to sediment-associated contaminants via their prey. Quillback rockfish are carnivorous, consuming reef-associated prey, organisms from the finer-grained substrata that often surround reefs, and wide-ranging pelagic prey passing over reefs such as Pacific herring (Hueckel 1980; Murie 1994; Murie 1995). It is possible that rockfish from the Foulweather Bluff area consistently consumed organisms higher in the food chain than from other locations, resulting in a greater biomagnification of Hg.

Unlike mercury, PCBs appeared to accumulate only in male rockfish from Elliott Bay and Sinclair Inlet. These accumulation patterns are somewhat equivocal, because of the low sample size from Sinclair Inlet and lack of older specimens from Elliott Bay. In future sampling we will target older fish from urbanized locations like Sinclair Inlet and Elliott Bay to determine the validity of this pattern.

There is no evidence from our data that PCBs accumulated in female rockfish. Indeed, for females, we observed the greatest PCB concentrations in nine- and 10-year-old fish from Blakely Rocks and Elliott Bay, with lower concentrations in older fish. Larsson et al. (1996) hypothesized that for "lean" species which reproduce repeatedly throughout their lifetime (like rockfish), females should accumulate lipophilic compounds such as PCBs until they begin reproducing, after which contaminants are reduced via transfer of lipids to eggs (Figure 4a). Males in this hypothesis would continue to accumulate contaminants since there is no significant loss of PCB-rich lipids to sperm.

The age at which female quillback or brown rockfish in Puget Sound begin reproduction is unknown. (Wyllie-Echeverria 1987) estimated the age of first reproduction in quillback rockfish at five years for California populations. Our anecdotal observations of gonad conditions indicate that quillback rockfish from Puget Sound probably do not mature any earlier than five years, and probably mature substantially later. Additionally, rockfish fecundity increases exponentially with fish age (DeLacey et al. 1964; Washington et al. 1978), suggesting that reproductive loss of PCBs in females may increase with age once reproduction begins.

According to Larsson's (1996) hypothesis, lean species should exhibit a greater gender-specific disparity in PCB accumulation than fatty species. Rockfish are considered relatively "lean." Lipid content of muscle-tissue in rockfish from our study was usually less than 1%; we have recorded salmon lipid concentrations exceeding 20% (O'Neill and West, this volume). If Larsson's (1996) hypothesis is correct, we would expect to see accumulation of PCBs in female rockfish until sometime after age five, after which the intake of PCBs through diet would be offset by loss of PCBs though reproduction. Our data from Elliott Bay generally support this hypothesis (Figure 4b), however, the relationship is somewhat confused by the low PCB concentration observed in one 12-year-old specimen.

It is clear that age, gender, and location are important factors to consider when evaluating or predicting mercury or PCBs in long-lived species like rockfish. The life span of quillback and brown rockfish in Puget Sound is unknown. However, we have estimated ages up to 60 years for quillbacks, and 70- to 80-year-old rockfish are not uncommon in Alaska (Victoria O'Connell, Alaska Dept. Fish and Game, unpublished data). All of our regression analyses were performed on fish younger than 35 years, which indicates that we have underestimated the full range of mercury PCB concentrations in rockfish from Puget Sound.

The strong location-specific accumulation patterns indicate that Sound-wide predictions using a single fish age:contaminant regression model to predict mercury or PCBs may not be accurate. Gender

and location-specific factors such as sediment contamination and food habits may contribute significantly to the regional variability in contaminants we observed.

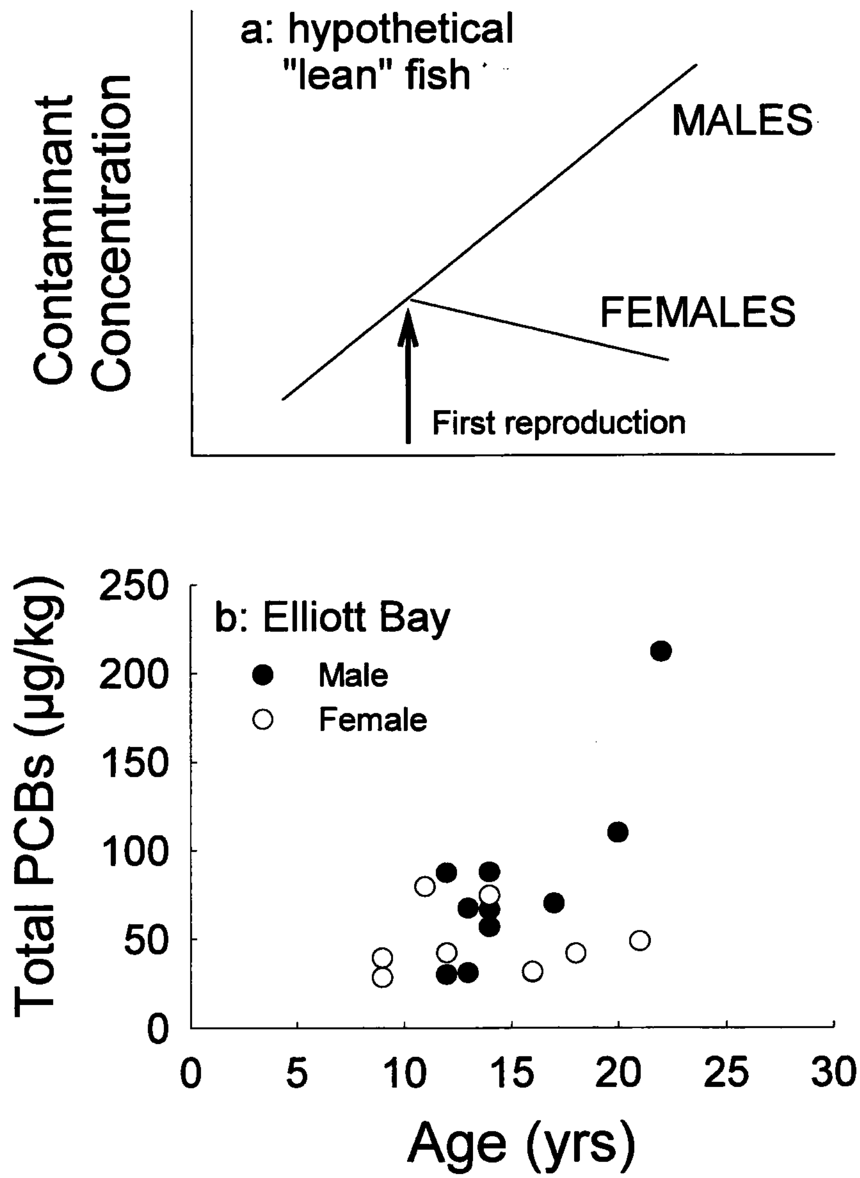

Figure 4. Hypothetical gender-specific accumulation patterns (a) of PCBs in "lean" fish that reproduce repeatedly throughout their lives (e.g., rockfish), adapted from Larsson et al. (1996), and gender-specific accumulation patterns (b) in quillback rockfish we observed from Elliott Bay, Washington.

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[iii] We have estimated ages of quillback rockfish to 60 years in Puget Sound.
[ii] We did not sample for organotins or dioxins.
[iii] Stepwise linear regression analysis with dummy variables was used to separate location effects.
[iv] Not shown in these analyses is the [Hg] for a single 60-year-old specimen taken from the San Juan Islands. That specimen had a [Hg] of 0.81 mg/kg and it was omitted from the regression analyses because of the large gap in data between it and the individual with the next lowest age (27 years).
[v] PCB results for Foulweather Bluff were not available as of this writing.

Managing Source Control Efforts in the Thea Foss Waterway, Tacoma, Washington

Mary Henley

City of Tacoma, Public Works Department Utility Services Engineering Division

Abstract

In 1994, the City of Tacoma entered into an Order with the Environmental Protection Agency (EPA) to develop a remedial action plan for contaminated sediments in the Thea Foss Waterway. The City of Tacoma has been identified by EPA as a Potentially Responsible Party because of municipal stormwater discharges to the waterway, which include drainage from approximately 25% of the area of the city. Achievement of source control must be accomplished before actual remediation of the sediments can occur. A number of studies are underway to determine which sources and contaminants have the potential for recontamination. For the storm drains, this includes low detection limits, whole-water sampling, and in-line sediment trap sampling (performed in cooperation with the Department of Ecology). Sample results will be used to develop input loadings to the WASP Contaminant Transport Model. Modeling results are being used to focus the city's source control efforts. Industrial inspections and implementation of Best Management Practices will be used to control sources to the extent possible. If ubiquitous levels of contaminants in urban runoff are found to pose a threat to recontaminate remediated sediments, the City will continue to work with regulatory agencies to develop a plan that will allow sediment remediation to proceed.

Contaminant Transport Processes in Thea Foss Waterway—Managing Source Control and Natural Recovery

Dr. Todd Thornburg

Hart Crowser, Inc.

Dana DeLeon

Cosmopolitan Engineering Group

James L. Martin

AScI Corporation

Abstract

Because of its long and diverse urban history, the Thea Foss Waterway in downtown Tacoma has accumulated PAHs, phthalates, mercury, PCBs, and other constituents at concentrations that exceed the Sediment Quality Objectives for Commencement Bay. Sources have historically included inputs from municipal storm drains, erosion of contaminated banks or upland soils, groundwater seeps, industrial discharges, and other sources. To evaluate the current status of source controls in and around the waterway, and to predict future trends in sediment concentrations, a contaminant transport model was constructed using EPA's Water Quality Analysis Simulation Program (WASP). Comprehensive field collection efforts have helped to define site-specific environmental conditions for the waterwa, and the physical, chemical, and biological input parameters required by WASP. In addition to sediment testing conducted during Pre-Remedial Design, extensive sampling of base and storm flows in municipal outfalls, tracer studies of advection and dispersion, water column chemistry, radioisotopic dating, biodegradation experiments, installation of pipeline sediment traps (in cooperation with the Department of Ecology), and in-water monitoring wells are among the studies that have been undertaken by the City of Tacoma. The model is being used successfully to understand the cumulative effects of diverse pollutant loads on the waterway, to help the City manage its source control efforts in the upland drainage basins, and to identify parts of the waterway that will naturally recover without the need for active remediation.

2B: Toxic Contaminants

Questions & Answers

Q: Regarding your data for Foulweather Bluff: Could the naval base in Hood Canal have anything to do with it? There is an extremely large current from Hood Canal that affects Foulweather bluff, and I thought that current might carry some mercury from the naval base to that location.

A: It's quite a ways away. Intuitively, I wouldn't expect that. But we have English sole samples that are from around the area of the Hood Canal Bridge. We don't see elevated levels of mercury in that species, although it is a different kettle of fish, sort of. But I do think that's quite a distance.

Q: Sandra, I'm assuming that this is true since you didn't mention it but, that there isn't any separate coded wire data for the delayed hatchery fish program.

O'Neill: There are coded wire tag data. These data show that when you sample in the winter when the fish should not be resident in Puget Sound, you get higher recoveries for south sound net pen fishes than you do for stocks from northern Puget Sound. This suggests that, in fact, the net pens are doing what they were intended to do. The use of net pens does appear to result in fish being more resident.

Q: Since your samples were composites of multiple fish, you weren't able to tease that out, I take it, in your data?

O'Neill: Not all the fish that we collect have coded wire tags on them. Our South Sound samples usually come from a mixed stock: some are wild and some are from hatcheries. We separated the fish in our composites so that hatchery fish were together in one sample and wild fish together in another. However, our composite hatchery samples may include some hatchery fish that were from net pens and some that weren't. For example, we might have had five fish in a composite and only one of them had a coded wire tag saying that it was from a net pen in southern Puget Sound.

Q: Jim, it's probably the same data but, one thing that struck me in looking at your rock-fish data was there may be differences in the population dynamics at these different locations. That is the age-structure, sex rations, and so on. Do you have enough data from any of these areas to be able to look at that issue?

West: I'll give you your five dollars later. Yes, actually, one of the fingerprints we're using to get at that is the growth rate data. And we do have good growth rate data for these locations, as well as many more, and we find varied location-specific growth rates, and some that are quite strikingly different. Our age-frequency data are not really usable because we don't apply our sampling in a manner that allows us to do that. We are essentially biased in the way we are collecting our samples for age frequency. But we are planning to use growth rate as sort of a fingerprint of a local regional stock. And actually there is a lot of interest in using that in order to try to demonstrate that these fish don't move around very much.

Q: Sandra, I was wondering about the discrepancy in PCB content in marine caught fish vs. fish caught in the river—whether it might possibly be explained by the osmoregulatory processes that the salmon go through. When they are heading back into fresh water, they tend to change the chemistry in their bodies. I was wondering whether that had any effect on that discrepancy or if that was considered, or what your views were on that?

O'Neill: Well, you've got me. Most of the contaminants that are in their tissue probably accumulated over a fairly long period of time. All I can tell you is I know the lipid content tends to

be lower in river fish. I don't know if the percent solids and things like that are that different. They don't look it, but I haven't run the tests statistically. But someone like Frieda Taub might be able to answer that. She's sitting over there. What do you think, Frieda?

Taub: I'm going to ask you another question, but it's related. When the salmon are caught on the high seas, before they approach the land, do they have high PCBs or low PCBs? Are they picking up the material either from the water or from food – presumably a lot of them are not feeding once they enter fresh water. Now there's been, I think, substantial studies showing that fish can pick up substantial amounts of PCB just across their gill surfaces, and there are some models that EPA has that could explore this. We could set the food input to zero and have PCBs in the water and it will tell us how much would come in through the gills, but I never believe mathematical models. I'd rather know what the fish are doing.

O'Neill: So you're suggesting that the PCBs are being accumulated quite rapidly, just as they enter Puget Sound?

Taub: Well somebody must have PCB values for salmon before they've been impacted by the rivers.

O'Neill: Well, the only other salmon PCB data that I've seen is some from Alaska for various fish species, and I think National Marine Fisheries Service did the analysis. They had PCBs in their tissues at similar concentrations as seen in Puget Sound. I didn't have lipid content data for these measurements and they were analyzed as congeners, , but just eyeballing them, they looked about the same. I would think that the PCBs are probably accumulating through the food chain in general. We did a little pilot study of herring in Puget Sound in 1995 where we sampled herring at Fidalgo Bay. We measured concentrations in whole herring and found that they have PCBs in their tissues that are up as high as 200 ppb. Those fish are not going out to the north Pacific. So there are PCBs in the food chain. The fact that they have such oily tissues and the PCBs are so lipophilic, my gut intuition would tell me that it is probably accumulated through the food chain over a period of time, rather than in the short time that they are swimming.

Taub: As far as the fresh water-salt water, I guess most of the studies that I'm aware of have really focused on the salt glands in the gills, and I do not know whether that would impact how they would handle PCBs.

O'Neill: A lot of the in-river fisheries, or river-mouth fisheries, are not in pure fresh water, and so they are more estuarine rather than in river. One of the big differences between our marine and in river comparison is that they're not balanced. The marine side of the sampling was only in central and southern Puget Sound whereas the in river part included some north Sound, so it's not really a balanced design.

Q: I would add to that last discussion, that we had the same question on the Columbia River, where we collected data from fish in the river and they had high concentration of PCBs and dioxins. No one had any ocean fish data, however, and still we had to go back to the Alaska data that Sandra just mentioned, which is not really a very good study for this purpose. I believe that NOAA out of Newport labs is attempting to get some ocean-caught data this year but, that kind of depends on whether or not there is any fishing seasons this year. I had one more question for Eric, if I might. Eric, you had a lot of data on metals concentrations and dissolved and total. I'm wondering about what you said at the end of your talk that concentrations were below the water quality standards. Did you take a look at the ratios of total to dissolved that you came across in your studies and compare those to the ratios that we have established in the state water quality standards to see what that variation might have been?

Crecelius: No, I didn't make a comparison with the ratios you're referring to. Sorry.

Q: The reason I ask, of course, is that we base our standards on EPA recommended criteria and we just changed those in November based on new recommendations from the EPA. I have no idea how they compare to your data but it would be interesting to take a look at that.

Crecelius: The EPA water quality criteria are based on, I believe, total recoverable metal.

Q: Well, they now have total to dissolved ratios that they have established for national recommendations, and we adopted those into our standards.

Crecelius: OK, in most cases the ratio of dissolved to total in these was typically what you might expect in what's been seen in other coastal areas in the world. Predominantly, for example, cadmium is usually 95% dissolved and lead is usually only 10 or 20% dissolved. So I don't think there were any surprises there.

Q: Jim, it's apparent that you don't want to catch that very smart, very old, 65-year-old fish in Sinclair Inlet. What does this mean in terms of human health. One milligram per kilogram is close to FDA's level of concern for mercury. Do people tend to catch the very young, dumb fish, or are those old, smart fish the ones that are actually caught and being consumed by humans, and therefore, where the risk may lie.

West: Well, there's a lot in that question. First of all, implicit is why aren't there older fish around and I don't know. Wayne Palsson might be able to shed some light on that. It may be the result of 100 years of fishing. And people tend to catch, or fishing gear tends to select the oldest, or the largest fish. Actually, Sinclair Inlet is not even a very good habitat for rockfish. The samples that we got were gotten fortuitously, but you're right in that the individual concentrations do exceed FDA limits, which are not strictly human health based limits. They have economic multipliers in them. More human health based criteria, or action limits are levels around 0.5 parts per million, which lots of our samples exceed. In fact, Sinclair Inlet was closed to bottom fishing because of some of these results. So, the Department of Health is aware of the data. We throw them at them as fast as we can. It's not very clear to us what are considered protective levels. We're not risk assessors or anything like that.

Q: I'm going to jump back into the fray on the PCBs in the coho and chinook again. At least on global scale, there is some evidence that has come out in the last five years or so that PCBs and pesticides have a global fractioning or partitioning with higher concentrations in open-ocean water being found at the higher latitudes compared to lower latitude. Is there any evidence that maybe chinooks, which have the higher PCBs, go further north in their migrations than do the coho? Is that a possible explanation?

O'Neill: I'm not sure about this, but I think that chinook, in general, migrate further out into the north Pacific than do coho as a species as a whole. I'm pretty sure that's right. But I don't know anything about contaminant levels in the north Pacific – north temperate vs. south temperate. Certainly some of the highest PCB sites on the West Coast for sediment contamination occur right in Puget Sound. The Duwamish Waterway is very contaminated. Hylebos Waterway and City Waterway or Thea Foss Waterway in Commencement Bay are very contaminated. If you went further north in Alaska, I don't know if there are some PCB hot spots, but I don't think you'd find really localized contaminants like you would here. PCB's can be transported by air to all kinds of remote areas, including high arctic lakes, so it's possible, but I would put money on trophic status in aged fish.

Q: Did you measure the methyl mercury as well?

A: No, we measured total mercury. It's too expensive to measure methyl mercury, but the best

information we have suggests that methyl mercury is about 95 or 96 percent of the total mercury. So, you can tweak those numbers down a notch if you're worried about 5 percent.

Q: Have you done any sediment samples for the last two species, because I think if you spent 10% of your budget on the sediment samples, you may have a clearer picture of the whole area you are studying, and probably, to help you to explain your data.

West: There's actually quite an extensive sediment monitoring effort that's already in place, and we use their data as best we can. For rockfish, where they live sort of precludes sedimentation. They live in rocky habitats or hard bottom, usually. So it's difficult. People tend not to break their equipment on the rocks. So we don't have very good sediment information or source information for rockfish, and we might not ever. But for salmon, I don't know that we would expect to be able to tie them to sediments because they move around so much and they are migratory. Your question pertains mostly, I think, to English sole, which Sandie will be talking about tomorrow where there's a really good, tight relationship between sediment levels and, I think, liver lesions and contaminants. She'll be talking about that.

O'Neill: I'm going to put a plug in for Ed's work, though. With the type of sampling that Ed is doing now, we will be able to make estimates of what proportion of central Puget Sound vs. northern Puget Sound is contaminated. And I have no doubt that we'll see, based on the sediment chemistry, that central and southern Puget Sound will overall be more contaminated than northern Puget Sound.

Q: I was just curious to know if you are using any of this information at all on the work that's being done on Puget Sound Navy Base and their Superfund site, because a lot of it could be complied in our efforts to try to negotiate the clean up there at Puget Sound Navy Base. It's probably going back to this morning, when they were saying that you guys with PSAMP could connect better. This is perfect for that, and all the information that you've collected in Sinclair Inlet. The minute rockfish were closed to the taking in Sinclair Inlet, we were on the Navy about that, and how it was showing up because it's very well known that they did a lot with mercury at the Navy base. It was left in open pits, and left for the tide to wash right out into the bay. So it all correlates, and you should definitely take a part in that process.

O'Neill: John, we've actually met with several Navy people from time to time, and given them a briefing, not just on the rockfish, but also on the English sole, and several of them have requested data sets from us. So they are aware of the data. Whether they tell you that they are aware of the data, I don't know. But they are definitely aware of the data. And the English sole data from there are quite interesting as well. We see elevated lead levels at Sinclair Inlet; we've let them know about that as well.

Q: As a biologist working on it, we get volumes of stuff from the Navy on this stuff, and if you could just maybe highlight some of this information for us and funnel that to us, it would really help.

A: One of the things that we are trying to make them aware of is that we can't see information that is sort of an unidentified flat fish, no age information, no species. The whole point behind what we're trying to do is show how these factors are important, and that if they're going to be taking their own samples and making comparisons, they need to account for those factors. So we haven't really met with them directly about that stuff. We're hoping it will happen through these kinds of forums.

Q: Well, they meet, but they are not real open. They invite you and they make it public, but, they would just as soon we not show up in a lot of cases, so, if we do show up, it's nice to have the information in hand when we're there.

PUGET SOUND RESEARCH '98

SESSION 2C

AQUATIC PLANTS AND ALGAE

Session Chair:

Thomas Mumford
Washington State Department of Natural Resources

Kelp Bed Habitats of the Inland Waters of Western Washington

J. Anne Shaffer
Washington Department of Fish and Wildlife

Introduction

Inland Washington waters from Cape Flattery east to Admiralty Inlet and south through Puget Sound are comprised of 1500 km of shoreline, and 266 km of kelp habitat. Combined, the kelp beds of the Strait of Juan de Fuca and Puget Sound are the majority of Washington's coastal kelp resources (Thom and Hallum, 1990; VanWagenan 1996). The Strait of Juan de Fuca makes up 300 km of this shoreline, and 134 km of kelp habitat. Puget Sound (from Admiralty Inlet south) consists of 1200 km of shoreline, and 130 km of kelp habitat. The Strait of Juan de Fuca therefore makes up 16% of the shoreline, but offers 50 % of the kelp habitat of the region.

Bull kelp, *Nereocystis luetkeana,* and giant kelp, *Macrocystis integrifolia,* are the dominant overstory kelp beds of Puget Sound and the Strait of Juan de Fuca. Within Washington waters, *N. luetkeana* can be found throughout Puget Sound, Strait, and coastal Washington. *M. integrifolia* is found along the central and western Strait of Juan de Fuca from Freshwater Bay and along the outer coast (Figure 1). Together these beds collectively support wonderfully complex nearshore assemblages of fish and plant life, and are considered critical habitats by local and national resource managers alike (Doty et al. 1995; Kvitek et al. 1989; Shaffer et al. 1995; Simenstad et al. 1988, 1979 a, b; U.S. Department of Interior 1995).

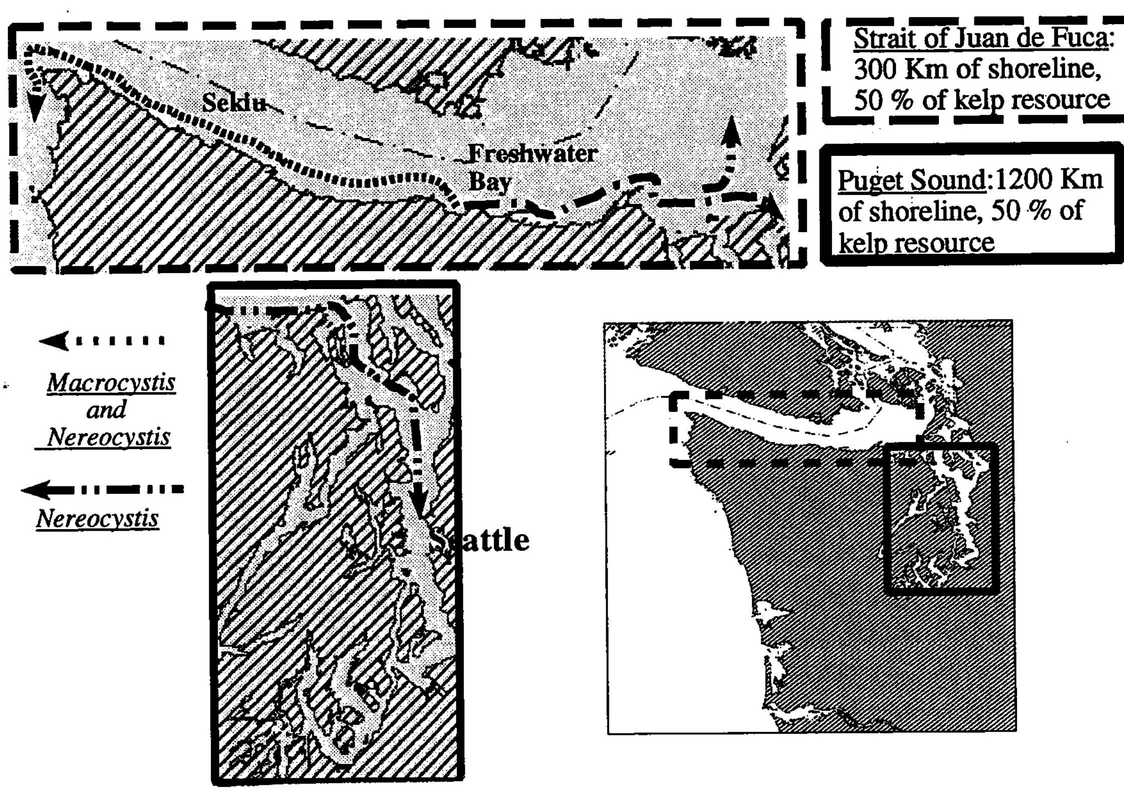

Figure 1. Kelp bed type and distribution, inland waters of western Washington.

The Strait of Juan de Fuca and Puget Sound also support, and are affected by, numerous human activities. They are heavily used transportation corridors for Puget Sound and Canada: cargo ships and fuel tankers ply their waters daily. Nearshore resources of Puget Sound and the Strait are therefore vulnerable to large oil spills, and have experienced a number of such events in the last twenty years. Non-point and point source input from sewage treatment plants, urban run off, and industrial sources such as paper mills are associated with cities and towns along the inland marine shoreline. Upland development is burgeoning along the shorelines of Puget Sound, with numerous impacts to nearshore environments (Canning 1995; Shreffler et al. 1995; Shipman 1995). Finally, timber extraction is one of the dominant economic bases for the Olympic Peninsula. Sediment contribution to the Strait of Juan de Fuca from timber management is a growing concern to nearshore resource managers. As these human interactions with the waters of the Puget Sound and Strait increase, so does the likelihood of nearshore habitat loss.

Despite the unique identity, heavy use, and critical habitat supported by Puget Sound and the Strait of Juan de Fuca, little is known about its nearshore vegetated habitats. The most basic information, including habitat composition and seasonal variation, is lacking for most Puget Sound and Strait kelp beds. Resource managers of Washington's inland marine waters are moving ahead despite this lack of information. Momentum for creation of Marine Protected Areas (MPAs) is increasing, and sites proposed within Washington include areas along the Puget Sound and the Strait of Juan de Fuca. Habitat restoration is also being considered for marine areas of the Puget Sound and the Strait. Both of these management tools require detailed knowledge of targeted marine habitats, including their composition and variability, to be effective (Lubchenco et al. 1997; Schiel and Foster 1992).

The goal of this paper then is to present findings of two pilot studies that define the basic features of the dominant understory habitats, including species composition and seasonal variation, of *Nereocystis luetkeana* and *Macrocystis integrifolia* kelp habitats of the Puget Sound and the Strait of Juan de Fuca. Focus is given to how such information might apply to MPA and restoration strategies for these kelp habitats.

Methods

Two pilot studies defined the basic features of the dominant understory habitats, including species composition and seasonal variation, of *Nereocystis luetkeana* and *Macrocystis integrifolia* kelp habitats of the Puget Sound and the Strait of Juan de Fuca. The first, which focused on seasonal variation in Puget Sound kelp beds, was conducted from February 1991 to February 1992. The second, which focused on seasonal variation of Strait kelp beds, was conducted from March 1996 to April 1997.

Two Puget Sound *Nereocystis luetkeana beds* and two each Strait *Nereocystis luetkeana* and *Macrocystis integrifolia* beds, hereafter termed *Nereocystis* and *Macrocystis* beds, were sampled seasonally for dominant understory vegetation density and percent cover, and substrate percent cover. Paired beds in 10-20 feet depth range were selected for each study. During each sampling, two 30 meter transect lines were randomly sampled within permanent locations within each bed. Five 1.0-m^2 quadrates were sampled along each line. Understory information (from the substrate to 1.0 m above the substrate) collected included total vegetation percent cover, dominant algal species relative percent cover and density, and substrate type percent cover.

In the Strait kelp bed study, densities of select macroinvertebrates, including kelp grazers and their predators, were also recorded. These included the green urchin, (*Strongylocentrotus drobachiensis),* red urchin (*S. franciscanus*) and purple urchin (*S. purpuratus*), northern abalone, (*Haliotis kamtschatkana*) and sun stars, (*Solaster* spp. and *Pycnopodia helianthoides*). All beds were sampled once every three to four months for a minimum of one year.

Total vegetation and dominant species percent cover and density were summarized for each bed and season. For Strait beds, invertebrate total for each bed type and season were tested for heterogeneity, and a Fisher Exact Test conducted to compare the invertebrate totals of the two bed types.

Results

Understory vegetation species composition, percent cover and densities varied with geographic location, kelp bed type, and season (Figures 2 and 3). In Puget Sound, total percent cover of *Nereocystis* beds varied from 30-80%. Strait *Nereocystis* bed percent cover ranged from 30–100%. Total percent cover within Strait *Macrocystis* beds ranged from 50–80%. Highest total percent cover was found in summer and fall, lowest in spring and winter. Individual species percent cover also varied by species, season, and site.

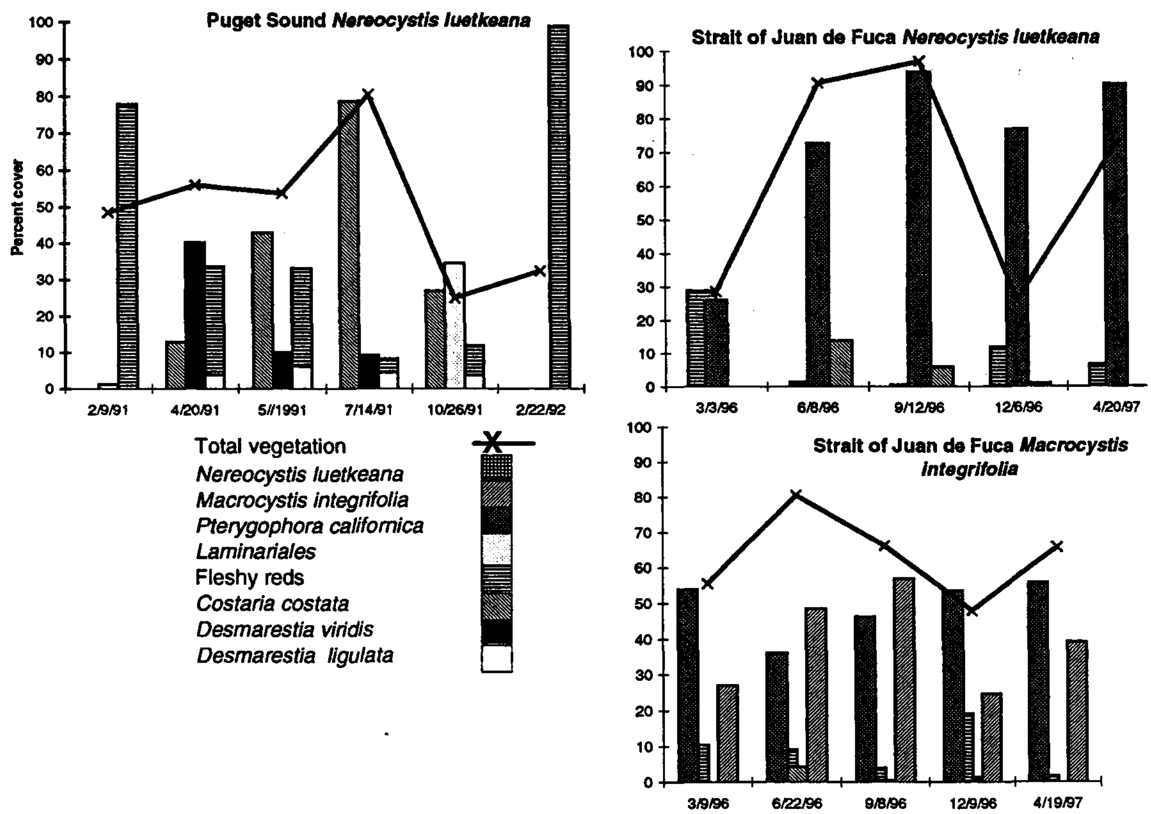

Figure 2. Percent cover of understory of kelp beds of inland waters of western Washington.

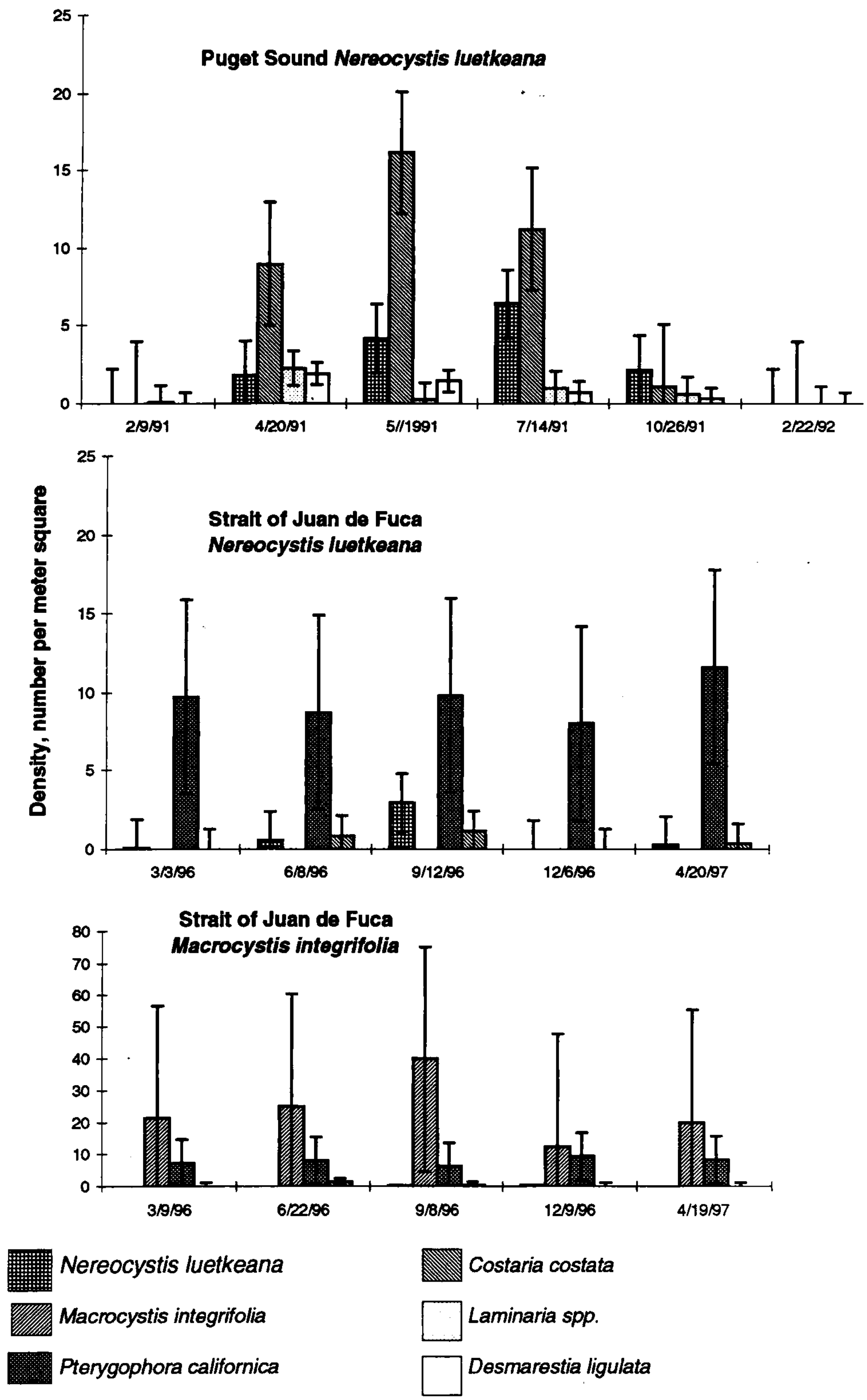

Figure 3. Density of dominant algae in inland waters of western Washington kelp beds.

Percent Cover

Percent cover of *Nereocystis* beds of both Puget Sound and the Strait of Juan de Fuca showed higher seasonal variation than found in Strait *Macrocystis beds* (Figure 2). For Puget Sound *Nereocystis* beds, total vegetation percent cover ranged from 30%–48% during winter months and when the beds were dominated by fleshy reds; 53%–55% during spring months when the beds were dominated by a mixture of *Costaria costata* and *Desmarestia* spp., and 25%–80% during fall and summer months, which were dominated by *Laminaria* spp, *C. costata*, and *Desmarestia* spp., Strait *Nereocystis* kelp beds showed similar trends in total percent cover, but the species composition was much different. Here, total percent cover ranged from 20%–30% during winter months, but the beds were dominated by *Pteropophora californica* and fleshy reds. Summer months had total percent covers of 90%–100% that were dominated by *P. californica*. Spring percent cover jumped to over 70%, again dominated by *P. californica*. *Nereocystis luetkeana* was not the dominant contributor to understory habitat in either the Puget Sound or Strait *Nereocystis* beds, and never comprised more than 2% of the relative percent cover.

Variation in total percent cover was much less striking in Strait *Macrocystis* beds, and never dropped below 50%. *Macrocystis integrifolia* and *Pterygophora californica* were the dominant algae during all months. *M. integrifolia* percent cover was highest in spring and summer months, when it contributed from 40%–58% of the total cover. *M. integrifolia* percent cover was lowest during winter months, and made up approximately 28% of the total cover. *P. californica* had higher percent cover than *M. integrifolia* during spring and winter, and ranged from 55%–58% of the total cover. Fleshy reds were also seasonally present in the *Macrocystis* beds, and contributed from 5%–20% of the total cover depending on season and site.

Kelp Densities

Average understory kelp densities varied dramatically by bed type, season, and species. Kelp densities within both Puget Sound and Strait *Nereocystis* beds showed the strongest seasonal differences, and ranged from 0 to 6.5 stipes/m^2 in Puget Sound beds, and 0–3.5 plants/m^2 in Strait kelp beds. Both areas had highest *Nereocystis* densities during spring and summer months. Again, other Laminarians made up the bulk of understory densities. In Puget Sound kelp beds, *Costaria costata* was the dominant algae for all but fall, and topped out with 17 stipes/m^2 during spring. In Strait *Nereocystis* beds, *Pterygophora californica* was dominant for all months sampled, with average densities hovering between 7–13 plants/m^2.

Kelp densities in Strait *Macrocystis* beds were dominated by *Macrocystis integrifolia* and *Pterygophora californica. M. integrifolia* densities varied with season: highest stipe densities were observed during spring and summer months. Average *Pterygophora californica* densities did not appear to change much with season, and ranged from 5–7 stipes/m^2 during all sampling dates.

Finally, correlation analysis on Strait kelp data revealed no significant relationship between *Macrocystis integrifolia* or *Nereocystis luetkeana* and *Pterygophora calfornica* density for individual beds or combined species beds ($r=-0.136$; $r=-0.028$, $n=90$; $p>0.20$ respectively).

Invertebrate Densities

Strait kelp bed invertebrate species composition and density varied substantially between and within the two types of kelp beds (Table 1). When sampling dates were combined, *Nereocystis* beds had significantly higher total number of invertebrates than *Macrocystis* beds (Fishers Exact Test, $G_{adj}=31.10$, $p<0.001$). *Nereocystis* beds had higher densities than *Macrocystis* beds for three of the five sampling dates, two of these dates were significantly different (spring and summer, ($G_{adj}=27.30$ and 4.44 respectively; $p<0.05$; Table 1).

Table 1. Fisher's Exact Test for total number of green urchin, *Strongylocentrotus drobachiensis,* red urchin, *S. franciscanus*, purple urchin, *S. purpuratus*, northern abalone, *Haliotis kamtschatkana,* and the sun stars, *Solaster* spp. and *Pycnopodia helianthoides* within *Macrocystis* and *Nereocystis* kelp beds along the Strait of Juan de Fuca.

Date	Total Number of Select Invertebrates					
	Freshwater Bay (Eastern Site)**		Sekiu (Western Site)**			
96/97	Macrocystis	Nereocystis	Macrocystis	Nereocystis	DF	Gadj
3 March	-	27	5	10	-	-
8 June	0	10	2	2	1	4.44**
12 Sept	2	7	1	13	1	1.98
9 Dec	0	2	19	9	1	3.34
4 April	0	20	40	30	1	27.30***
Total	2	66	67	64		31.10***

. (*=P<0.05 **=P<0.01 ***=P<0.001)

The green, red, and purple urchins, *Strongylocentrotus drobachiensis, S. franciscanus* and *S. purpuratus*, northern abalone, *Haliotis kamtschatkana* and the sun star, *Solaster* spp. were the most common invertebrates in the *Nereocystis* beds, and were found in low numbers (Figure 4).

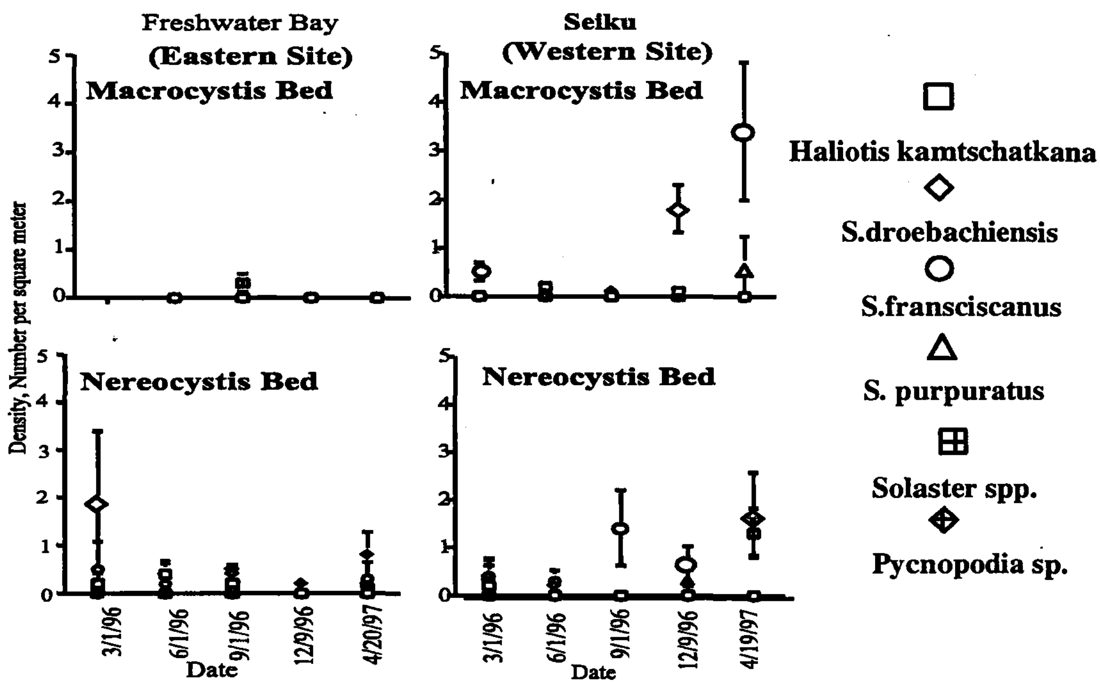

Figure 4. Average invertebrate densities (with standard error) for kelp beds of the Strait of Juan de Fuca.

Substrate

Substrate of Puget Sound and Strait kelp beds varied with geography and kelp type. Puget Sound *Nereocystis* beds were made up largely of cobble, with pockets of sand and shell. Strait kelp beds substrates were dominated by boulder and rock, with small patches of sand and gravel (Figure 5). Strait *Nereocystis* beds were dominated by boulders; *Macrocystis* beds were dominated by boulder

and rock. Both Puget Sound and Strait *Nereocystis* beds offered a broader mixture of substrate types than Strait *Macrocystis* beds.

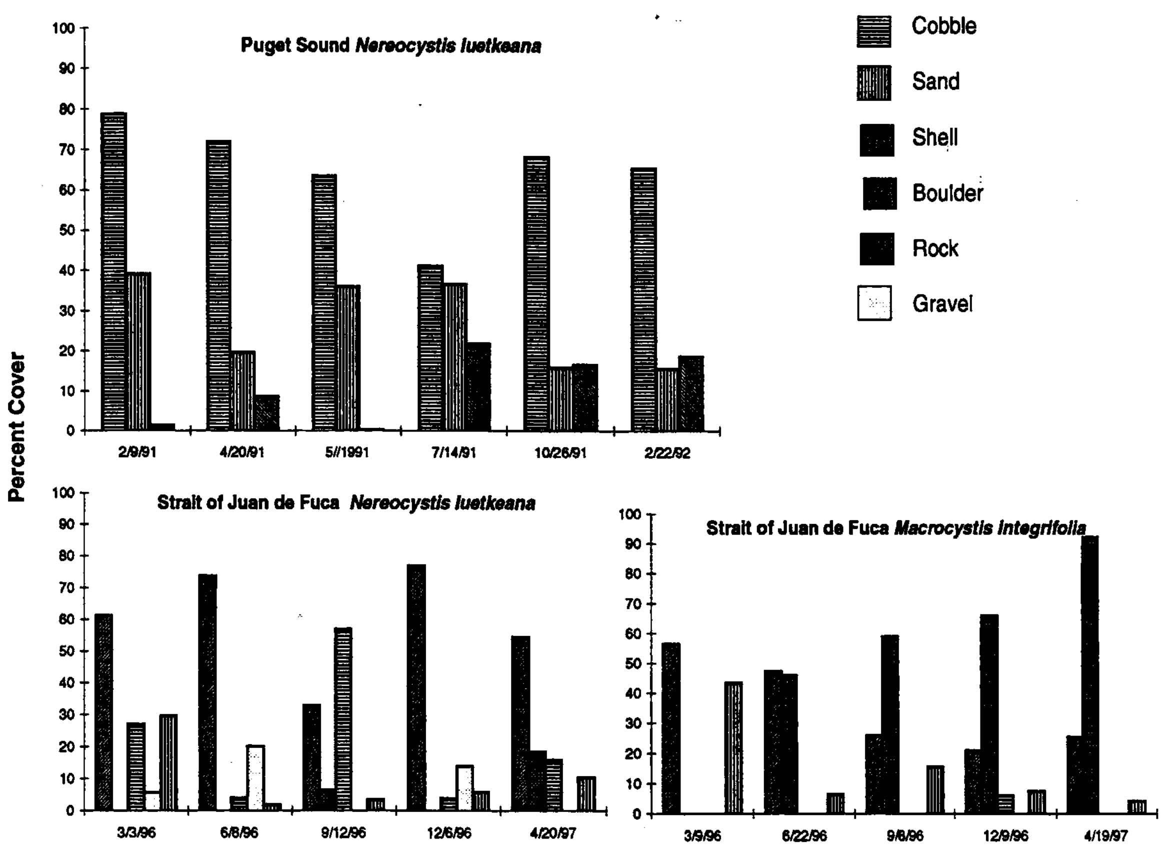

Figure 5. Substrate types for kelp beds of inland marine waters of western Washington.

Discussion

Comparing the two geographic regions and kelp bed types summarized in this work, it becomes apparent that they share both similarities and differences. Similarities are most evident in the dramatic seasonal variation in total percent cover of each of the habitats, and in the *Nereocystis* beds of the Strait and Puget Sound, the minor contribution of the overstory species to the physical structure of understory habitats.

The similarities in seasonal variation observed in kelp communities of this study are also consistent with observations for other regions, and may be partially dictated by light, water temperature, physical and biological disturbance, and nutrient supply (Foster and Schiel 1985; Shaffer and Parks 1994; Zimmerman and Kremer 1984).

A number of important differences were observed between the kelp beds in Puget Sound and the Strait. Puget Sound kelp beds show dramatic seasonal variation in their understory community, and shift from large Laminarian species during spring and summer to fleshy red algae during winter months. While similar changes in total percent cover are seen in kelp beds with the same overstory species in the Strait, the dramatic changes in the understory composition were not.

Important differences observed between *Macrocystis* and *Nereocystis* beds include: 1) *Macrocystis* beds appeared more seasonally stable, and had a more diverse macroalgal profile than *Nereocystis*

beds; 2) within *Macrocystis* beds, the overstory plant appeared to make up more of the understory habitat than in *Nereocystis* beds; 3) *P. californica*, a perennial understory species not visible from the sea surface, was a dominant feature of both Strait bed types, and of Strait *Nereocystis* beds in particular; and 4) in the Strait beds, densities of invertebrates selected for observation differed between bed type, with grazers and their predators having higher densities, total numbers, and number of species in *Nereocystis* beds than in *Macrocystis* beds.

There are many plausible reasons for these differences, including geographic location and life history strategies of the kelp and invertebrate species involved. Differences in community structure between Puget Sound and Strait kelp beds are likely the result of geography. A large sill isolates Puget Sound from waters of the Straits of Georgia and Juan de Fuca. This circulatory barrier seasonally limits both nutrients and phytoplankton between the water bodies (Strickland 1983) and is theorized to be a limiting factor in the distribution of *Macrocystis integrifolia* to the central and western Strait (Mumford, pers comm.). The complex oceanographic patterns and physical attributes, including oceanic currents and wind and wind exposure of both the Puget Sound and Strait, also undoubtedly play a role in defining community structure of their respective kelp habitats.

Differences observed between Strait kelp beds may be attributed to geographic location and plant life histories. The Strait of Juan de Fuca is at its western end mostly oceanic, and estuarine at its eastern end (Strickland 1983). This gradation is undoubtedly expressed in the kelp bed communities along its shores. Kelp life history also plays a significant role in differences observed. *Macrocystis integrifolia* is a perennial, and is structurally much more diverse than *Nereocystis luetkeana* (Abbot and Hollenberg 1976). As evidenced here, it offers more surface area than *Nereocystis* does, and it does so throughout the year. The *Macrocystis* beds and their understory community, therefore, appear more stable than the *Nereocystis* beds. *N. luetkeana*, on the other hand, is an annual, and is structurally much more sparse than *M. integrifolia*. As these data show, it therefore offers less structure to the understory, and much greater seasonal change in its understory community.

Invertebrate densities may also be attributed to overstory kelp species and life history. Kelp-derived carbon greatly influences the subtidal and intertidal communities of kelp beds, and is the basis for complex food chains (Bustamante and Branch 1996; Duggins et al., 1989; Simenstad et al. 1993). The larger variation in understory cover within *Nereocystis* beds may indicate a larger relative contribution of detritus (e.g., 'drift algae') available to grazers, and may partially account for higher numbers of selected invertebrates. This higher seasonal variation in *Nereocystis* understory may subsequently support more invertebrates and a higher invertebrate diversity through increased food resource availability and biological disturbance. Alternatively, change in algal cover may also allow for greater water circulation, decreased biological disturbance, and so greater settlement of grazers and their predators.

Substrate undoubtedly also plays a role in defining the understory community. The greater substrate diversity of *Nereocystis* beds may offer a broader array of habitat types, and result in higher numbers and species of invertebrates as noted in this study.

Further, targeted invertebrate densities appear to vary between differ with geographic areas within the Strait of Juan de Fuca. This further illustrates the strong variation that is possible within a kelp bed type, and the importance of both species and location for kelp bed function. Reasons for these differences are many, and may include relative location to the Strait entrance and associated oceanic waters, substrate type, and relative exposure to, and impacts from human activities including fishing, upland development and associated non-point pollution.

This geographic gradation in the relative stability and community composition of the kelp understory has intriguing implications to habitat function. In short, while they both change dramatically with season, *Nereocystis luetkeana* beds of Puget Sound are not the same as those in the Strait of Juan de Fuca, and so may not be interchangeable. Furthermore, saving a kelp bed in one region may not replace what has been lost in another. Also, the interaction between the seasonal

stability of the algal species that make up the kelp bed, and invertebrates that use it as illustrated in abundance of targeted invertebrate species of this study, is an important point when preserving and restoring kelp beds.

Along the same lines, *Nereocystis* beds of the Strait of Juan de Fuca are not the same as *Macrocystis* beds. The lower seasonal changes in total percent cover, consistently equal or higher total percent cover throughout the year, and the higher diversity of the understory macroalgal community of *Macrocystis* beds may offer a more stable environment for guilds that depend on the kelp habitat for refuge and food, including phyto-and zooplankton, shellfish and finfish, sea otters, and birds than *Nereocystis* beds. These guilds are often targeted in marine protected areas and kelp restoration activities. Each has different and undoubtedly complex requirements from these habitats. It quickly becomes apparent that well defined preservation and restoration goals, as well as detailed site-specific habitat information, are needed prior to implementing such management activities if success is to be achieved.

In summary, there are a few similar trends, and a number of striking differences within and between kelp beds of Puget Sound and the Strait of Juan de Fuca. The variation in understory communities observed with bed type, location, and season underscores the need to define the specific goals of preservation and restoration activities prior to implementing management activities such as Marine Area Preserves and kelp bed restoration. Preservation and restoration efforts will be less effective if species targeted for restoration and/or preservation are not well defined relative to the geographic location and species of kelp habitat being considered. Furthermore, variation found in this study underscores the need for detailed long term studies if habitat restoration and preservation are to be successful.

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Puget Sound's Eelgrass Meadows: Factors Contributing to Depth Distribution and Spatial Patchiness

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Introduction

The purpose of the present paper is to examine light requirements of eelgrass (*Zostera marina* L.) and discuss factors leading to eelgrass distribution and patchiness using a large data set on depth distribution in Puget Sound. Eelgrass is a rooted flowering plant that forms meadows in the shallow waters of Puget Sound. It is the most widely distributed species of seagrass in the temperate areas of the Northern Hemisphere (Phillips and Menez 1988; Wyllie-Echeveria and Thom 1994). Over the past 20 years, scientists, regulators, and the public have become increasingly aware of the importance of eelgrass meadows to the Puget Sound nearshore ecosystems. Eelgrass forms habitat for a diverse assemblage of animals, including Dungeness crab, juvenile salmon, and herring (Phillips 1984).

Multiple environmental factors interact to control the distribution of eelgrass, including light, substrata type, salinity, and wave action. Simple biophysical models are now being developed that predict both the presence and, to a lesser degree, the abundance of eelgrass, based on an understanding of the relationship between the controlling factors and eelgrass requirements.

Pollutant discharges to marine waters and coastal development projects place constant pressure on healthy and viable eelgrass meadows. Studies we have been conducting over the past four years have revealed large areas in Puget Sound where environmental conditions appear to be favorable for eelgrass, but where eelgrass is not present or in very low abundance. We have been able to explain some of this variability as effects of past or present disturbances at these sites. For example, eutrophication, shading, propeller wash, and disturbance by foraging crabs have been documented to cause fragmentation of existing meadows (Thom et al. 1988; Simenstad et al. 1997). Recovery of these areas may be limited by some other environmental factors.

Light is of paramount importance in determining the distribution of eelgrass (Olson and Thom 1997). Over the past four years, there has been a growing research effort to understand the effects of shading from overwater structures on eelgrass (Simenstad et al. 1997). Models are currently being developed to help predict the effects of proposed structures on the distribution of eelgrass (e.g., Olson et al. 1997). We have developed eelgrass cover maps and a large data set on eelgrass depth and density through studies conducted near ferry terminals for the Washington State Department of Transportation (WSDOT). These data allow us to draw some general conclusions about the effects of light availability and quality on depth distribution and about factors contributing to the spatial patchiness of eelgrass in Puget Sound.

Study Sites

The field studies were conducted near the following seven Washington State Ferry terminals that span north and central Puget Sound: Anacortes, Port Townsend, Clinton, Kingston, Edmonds,

Southworth, and Vashon Island (Figure 1). Controlled productivity-irradiance studies were conducted in outdoor flowing seawater tanks at Battelle Marine Sciences Laboratory located at the mouth of Sequim Bay.

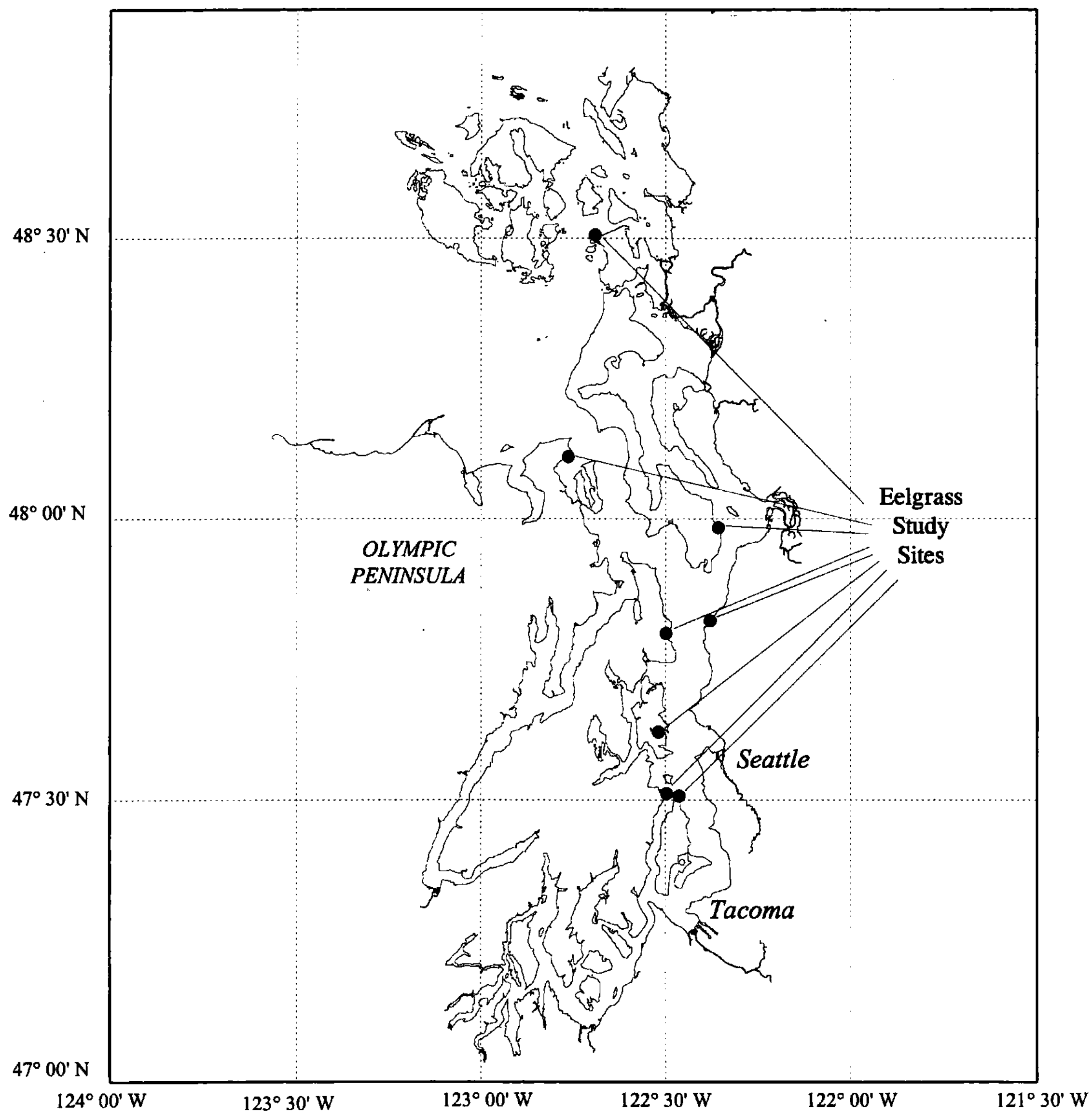

Figure 1. Location of eelgrass study sites in Puget Sound, Washington.

Methods

Eelgrass Mapping and Density Measurements

We employed video survey techniques (Norris et al. 1997), aerial photographs, and systematic diver surveys to accurately map eelgrass at the seven terminals (Thom et al. 1997). Divers ground-truthed the aerial photographs by sampling eelgrass density within triplicate 0.25-m^2 quadrats placed at 5- to 10-m intervals along transects. Depths measured by divers were calibrated to predicted tides each day. In total, the surveys produced 1,348 density-depth measurements.

In addition to density measurements, divers recorded any factors that might affect the abundance of eelgrass such as animals, propeller wash, and anchors chains at the seven terminals. At most sites, divers also noted the presence of seaweeds in the quadrats, in particular *Ulva* spp. To partially test the relationship between *Ulva* and eelgrass, we performed a 2 x 4 χ^2 test on data from one of the sites (Southworth) that showed an observable *Ulva*-eelgrass interaction. The test evaluated the observed frequency of *Ulva* relative to the expected frequency of *Ulva* within four eelgrass cover classes using the 212 observations from the site.

Net Productivity-Irradiance (P-I) Experiments

Over the period of 1991 to 1994, the relationship between eelgrass photosynthesis and level of photosynthetically active radiation (PAR) was experimentally determined using short-term (i.e., 2-hr) incubations of leaf sections (Simenstad et al. 1997). Leaf sections were placed in 1-L bottles filled with seawater and incubated under ambient PAR and sea temperature. Experiments were conducted several times during winter, spring, and summer. Five replicate bottles containing eelgrass along with five replicate water-only controls were incubated during each experiment. Ambient PAR was recorded continuously during each experiment using a Licor quantum sensor.

Light Attenuation

In August 1997 and February 1998, we measured PAR profiles by depth at five sites in Eagle Harbor, Washington. The sites ranged from relatively quiescent areas in the middle portion of the Harbor where eelgrass was very sparse, to an exposed, well-flushed area (Creosote Point) where eelgrass meadows were lush. At each site, we measured PAR at 0.5-m depth intervals between the surface and the bottom using a Licor spherical quantum sensor. Measurements were made between 10 a.m. and 3 p.m. These sites are likely representative of the range of attenuation found in nearshore areas of Puget Sound; however, verification through much more widespread sampling is needed.

Results and Discussion

Eelgrass Density and Depth Measurements

The depth vs. eelgrass density data from all seven sites showed that eelgrass reaches its greatest shoot density at about -2.5 m relative to mean sea level (MSL) (Figure 2A). We use MSL here because it relates to the average depth of water over eelgrass meadows throughout the year. To convert from mean lower low water (MLLW) to MSL, we used the relationship of MLLW + 2 m Å MSL. Eelgrass was generally not found below -7 m MSL. The greatest depth at which eelgrass was found varied between -5 m and -7 m MSL. Of note is that there were numerous bare patches within the depth range for eelgrass. Also, it is worthy to note that eelgrass typically grows to a larger size with increasing depth and will naturally form beds that are less dense, but these deeper beds still maintain a high bottom cover (Thom 1990). Above about -1.0 m MSL (+1.0 m MLLW) eelgrass is limited by other stressors, the strongest of which is desiccation.

Net Productivity-Irradiance Experiments

Light controls eelgrass photosynthesis, and thereby the growth and spread of the plant. This can be demonstrated using the productivity-irradiance (P-I) curves developed in the laboratory studies. The P-I curves (Figure 3) indicate that photosynthetic rate increases rapidly up to an irradiance level of about 300 $\mu M/m^2/sec$. Although the photosynthetic rates during summer, spring, and winter all peaked at approximately the same irradiance, the peak winter rate was approximately six times greater than the summer rate. The spring rate was intermediate. Our observations indicate that the plants are narrower and greener in winter than in summer. We suggest that the plants are far more efficient at utilizing available light energy in winter, which may be due to a more efficient winter morphology. Respiration rate is also likely to be lower in winter, because of lower temperatures.

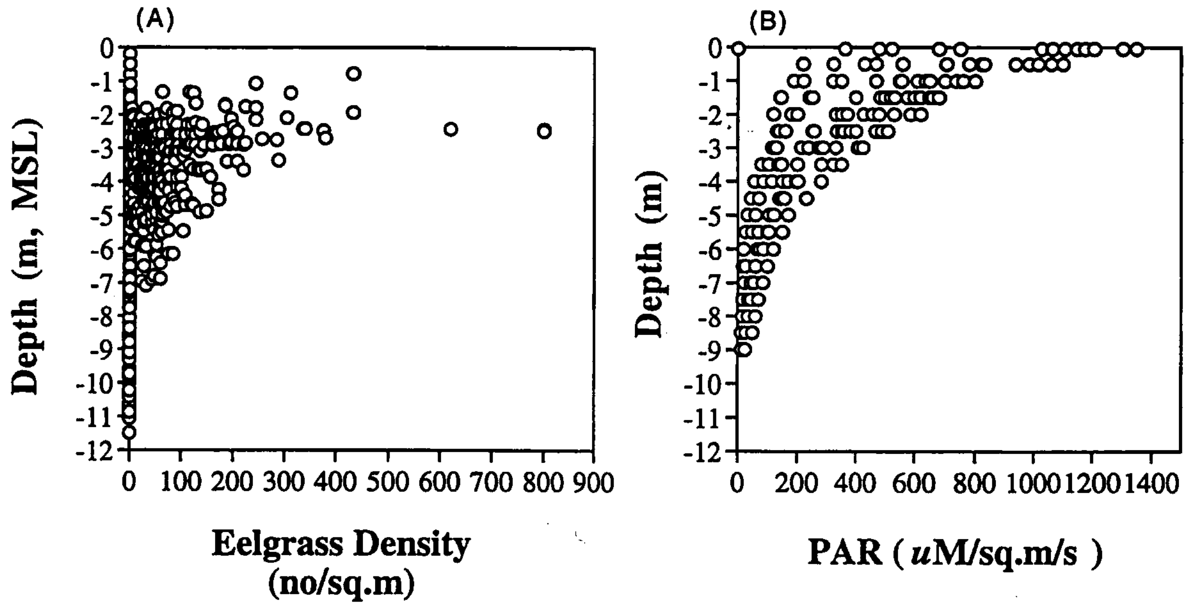

Figure 2. (A) Eelgrass shoot density vs. depth from diver sampling at the seven study sites; (B) PAR attenuation curves for sites in Eagle Harbor.

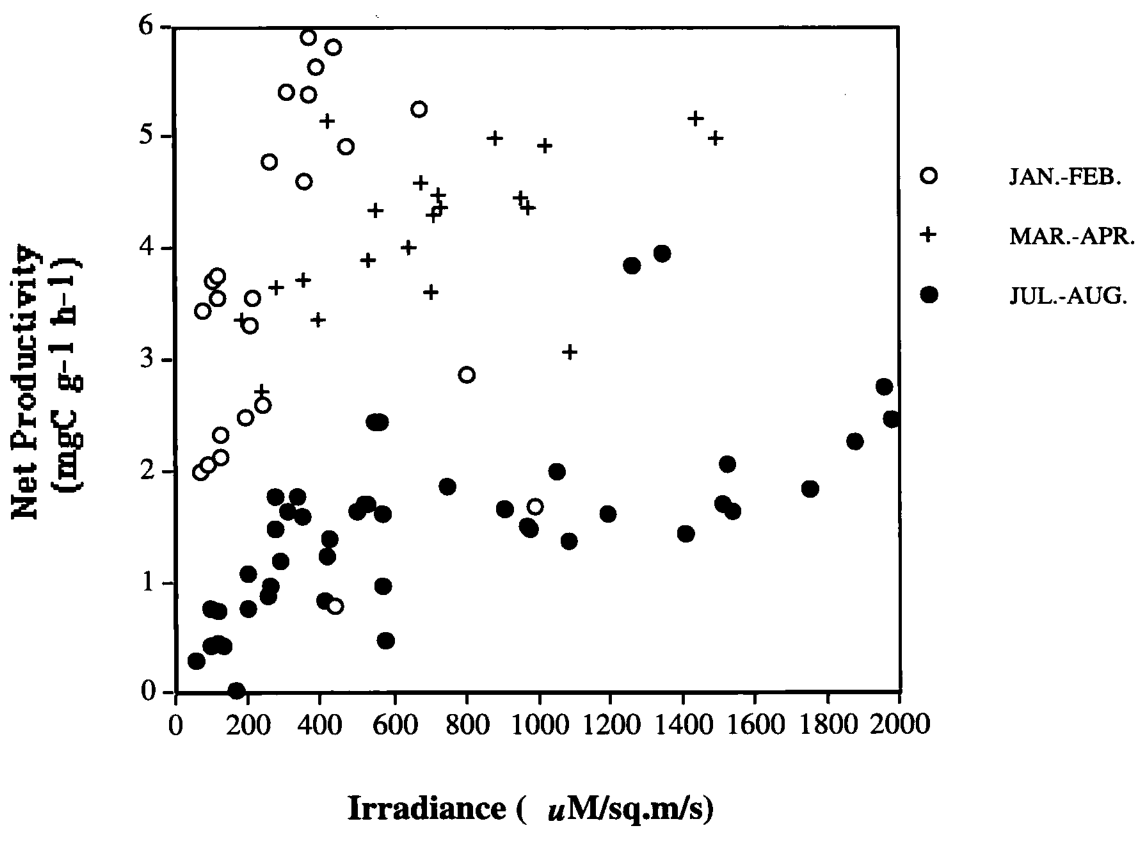

Figure 3. Net productivity vs. irradiance curves from short-term incubations of eelgrass leaf sections.

Light Attenuation

Coupled with light attenuation and eelgrass density information, the P-I curves are useful in evaluating the light requirements for eelgrass in Puget Sound. The mean light attenuation coefficient (K_d) at Eagle Harbor was 0.46 (SD = 0.13; range 0.28 to 0.80; n = 15), which is typical of many temperate estuarine systems (Kirk 1994). The attenuation curves show strong attenuation between the surface and approximately -4.5 m below the water surface, and that this corresponds with a strong decrease in maximum eelgrass density recorded at each depth (Figures 2A, 2B).

Although the attenuation curves were not collected from the sites where eelgrass was sampled quantitatively, the curves may be representative of light conditions in the northern and main basins of Puget Sound. Hence, general comparisons can be made. Maximum eelgrass shoot densities occurred where instantaneous, mid-day PAR levels were between approximately 100 and 550 $\mu M/m^2/sec$ (median Å 325 $\mu M/m^2/sec$). Lowest shoot densities occurred at PAR levels <150 $\mu M/m^2/sec$. Below about 100 $\mu M/m^2/sec$, no eelgrass was observed.

These results indicate that, on average, instantaneous mid-day PAR greater than about 150 $\mu M/m^2/sec$ is required to maintain eelgrass growth. Instantaneous PAR of approximately 325 $\mu M/m^2/sec$ is required to support maximum densities. These results are in accord with those of Simenstad et al. (1997) where long-term growth studies in flowing seawater tanks and long-term *in-situ* growth studies were used to develop light requirements for eelgrass. They also found that spring and summer were the critical periods of the year, when the plants are undergoing rapid growth, and are also storing carbohydrates in the rhizome. Carbohydrate reserves are then used to maintain the health of the plants during the fall and winter (Burke et al. 1996).

Eelgrass Mapping and Spatial Patchiness

A map of eelgrass distribution near the Vashon Island Terminal reveals the typical patchy nature of eelgrass at most of the sites (Figure 4). The loss of eelgrass at ferry terminals has been explained by Simenstad et al. (1997) as a result of historical disturbance during dock construction, shading, disturbance during maintenance operations, and propeller wash. They also noted disturbance by burrowing animals such as Dungeness crab, whose abundance was enhanced under the terminals. Areas outside the general region of the terminal were also patchy, but likely not because of terminal-associated effects.

We suggest that some of the observed fragmentation might be caused by an overabundance of seaweed biomass initiated by inorganic nitrogen loading. There is a growing awareness that *Ulva* spp. blooms occur in response to increased loading of inorganic nitrogen to nearshore systems (Short and Wyllie-Echeverria 1996). Divers reported finding a large abundance of *Ulva* spp. at virtually all sites. *Ulva* was very dense at Kingston, Vashon, and Southworth. Dense mats of *Ulva* have been shown to shade and smother eelgrass in Puget Sound (Thom et al. 1988) and New England (Short et al. 1995). In Puget Sound, impacts to eelgrass from *Ulva* have been observed in west Seattle (Thom et al. 1988), near Port Townsend (Chimacum Creek; R.M. Thom personal observation), and Seahurst Bight (Thom and Albright 1990).

Results of the 2 x 4 χ^2 test on data from Southworth indicated that there was significantly more *Ulva* present in areas with no eelgrass cover and significantly less *Ulva* present in areas with the greatest eelgrass cover (Table 1). Depth was also shown to be a factor, with more *Ulva* than expected in shallower depths and less *Ulva* than expected at deeper depths. These results allow us to at least put forth the hypothesis that there is a statistically significant negative interaction between *Ulva* and eelgrass. We believe that the hypothesis would hold for most of the sites we sampled.

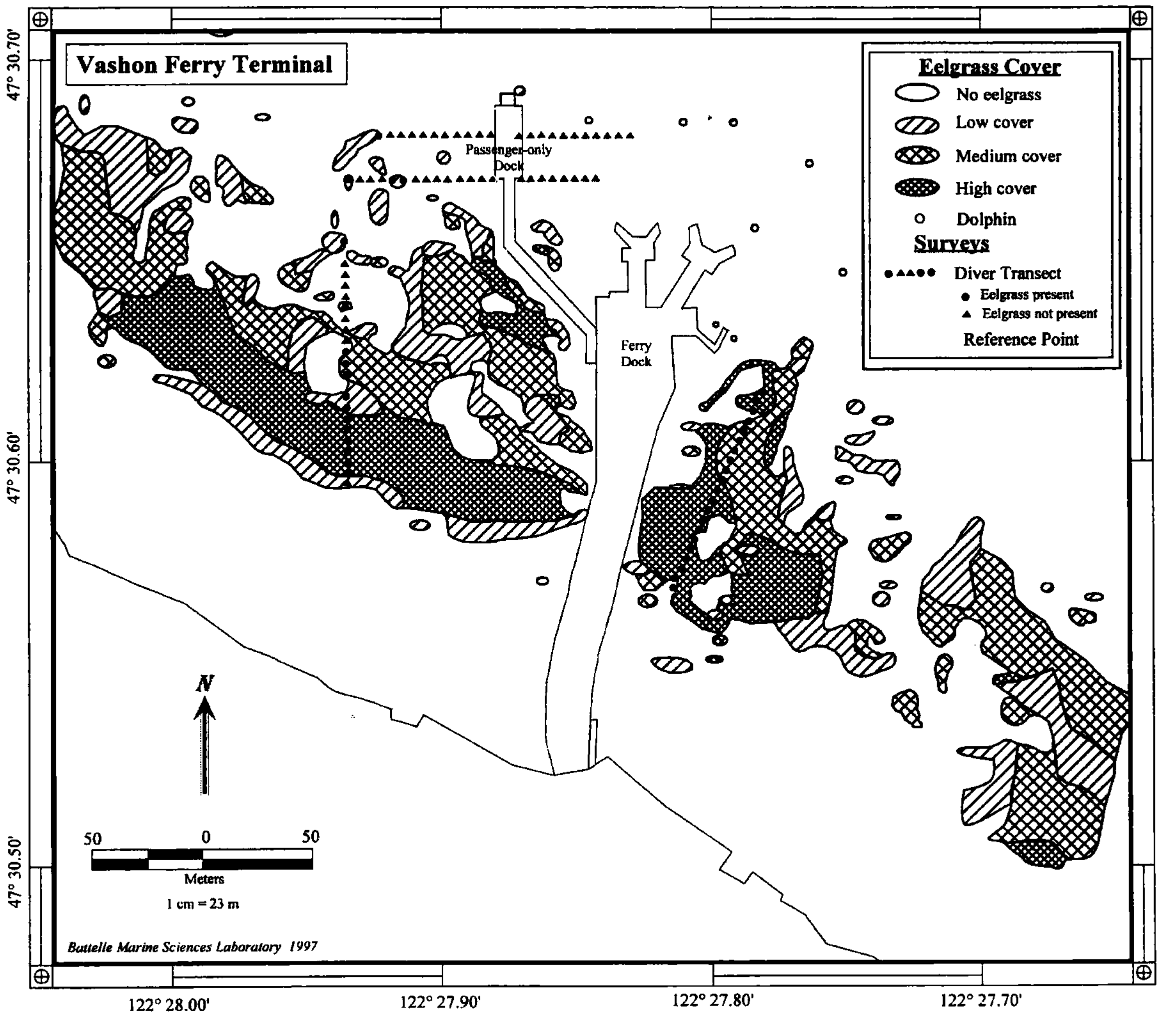

Figure 4. Map of eelgrass cover at Vashon Island ferry terminal study area (from Thom et al. 1997). Diver transects are shown, along with reference points.

Table 1. Results of analysis of the presence of *Ulva* spp. and eelgrass at sampling points at Southworth. Values are number of sampling points. Eelgrass cover is as in Figure 2.

	Eelgrass Cover				
	none	low	medium	high	total
Ulva present	116	3	3	1	123
Ulva absent	26	7	17	39	89
Total	142	10	20	40	212

Conclusions

The results of studies on light requirements provide some help in assessing impacts from proposed overwater structures on eelgrass and in determining the light level necessary to maintain eelgrass. The modeling efforts by Simenstad et al. (1997) and others will provide quantitative tools for calculating the effects of structures on eelgrass in the future. However, at present, we can say that maintaining at least 150 $\mu M/m^2/sec$ during mid-day throughout the year will likely allow eelgrass to persist. Maximum

eelgrass density would require about 300 µM/m^2/sec. Based upon previous work, the critical period for light is spring and summer, when the plants build energy reserves. Simenstad et al. (1997) found that integrated daily PAR of 3 M/m^2 is required to maintain healthy populations. This means that the 300 µM/m^2/sec would have to be reaching plants for an average of about 3 hr/day.

Obviously, far more light attenuation measurements close to sites where depth and density measurements have been taken are needed to verify our findings. However, the much simpler measurement of Secchi depth (Z_{sd}) can be used to estimate attenuation (Kirk 1994), and is a key monitoring parameter in Chesapeake Bay (Batiuk et al. 1992). A simple relationship between the vertical attenuation coefficient and Secchi depth is $K_d = 1.44/ Z_{sd}$ (in Kirk 1994). Using this equation, the minimum attenuation coefficient from Eagle Harbor, 0.28 m^{-1}, yields a Secchi depth of 5.1 m. The maximum depth limit of eelgrass in our study (-7 m MSL) used as a surrogate for Secchi depth (as is done in Chesapeake Bay) converts to an attenuation coefficient of 0.21 m^{-1} using the above equation. Finding a strong correlation between Secchi depth and the lower limit of eelgrass would be very useful in managing water quality and eelgrass health in Puget Sound. Knowing this relationship would allow managers to establish a Secchi depth that is "protective" of eelgrass health.

At present, Secchi depth data are collected monthly by the Washington State Department of Ecology, but their sites are generally too distant from eelgrass meadows to be directly useful. There is likely a difference in water clarity caused by nearshore plankton and suspended particulates that would make conditions over the meadows differ from those in deeper offshore areas. Our recommendation would be to establish new monitoring sites closer to shore in areas where eelgrass is abundant. We further recommend that measurements be taken more often (e.g., weekly) during spring and summer at these sites.

We suspect that patchiness of the meadows might be related to a variety of factors, but that *Ulva* blooms are likely responsible for some of the fragmentation. Thom and Albright (1990) showed that low nutrients limit seaweed production in nearshore areas in Puget Sound. This suggests that nearshore areas are susceptible to large increases in seaweed biomass caused by increased nutrient loading from the land. Data show that nutrients are extremely high from small streams entering the beaches where *Ulva* problems have been observed (Thom et al. 1988; Thom and Albright 1990). The eelgrass patchiness observed in concordance with *Ulva* biomass might be a first indication of such problems being caused by eutrophication in Puget Sound.

The Chesapeake Bay Estuary program has as a principal goal the restoration of seagrass meadows, and uses eelgrass depth distribution as a key monitoring parameter of water quality (Batiuk et al. 1992; Dennison et al. 1993). Certainly, eelgrass can be used for the same purpose in Puget Sound. Monitoring light attenuation along with the eelgrass lower depth limit, *Ulva* distribution, and degree of fragmentation of meadows would provide a powerful data set. Coupling this with sampling of nutrients in the vicinity of the sites would provide a way to integrate our understanding of the changes taking place in the watershed with the health of Puget Sound ecosystems.

Acknowledgements

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Monitoring Basal Area Coverage of Eelgrass in Port Townsend Bay

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Introduction

Seagrass meadows are a critical component of marine ecosystems throughout the world (Phillips and McRoy, 1980; Larkum et al., 1989; Simenstad, 1994). Documenting changes in seagrass distributions can be used to assess nearshore ecosystem health (Dennison et al., 1993; Dobson et al., 1995). Seagrass monitoring programs should be cost-effective, statistically valid, and capable of detecting changes over time (Iredale and Ferguson, 1995; Mumford et al., 1995; Lee Long et al., 1996).

In Puget Sound the seagrass *Zostera marina* (commonly referred to as "eelgrass") is ubiquitous along shorelines from the low intertidal zone down to a depth of about 6.6 m below mean lower low water (MLLW) (Phillips, 1972). To protect Puget Sound eelgrass habitat the Washington State Department of Fish and Wildlife (WDFW) has a "no net loss" policy (Fresh, 1994). Any waterfront construction project that may impact eelgrass habitat must first obtain a Hydraulic Project Approval, which may require mitigation (Fresh, 1994; Thom, 1994). The Washington Department of Natural Resources monitors eelgrass habitat in the low intertidal zone by direct beach observations and aerial surveys (Mumford, 1994). There is no systematic monitoring of Puget Sound eelgrass below MLLW.

In July 1994, the Port Townsend Marine Science Center added semi-annual (summer and winter) underwater video (UV) eelgrass surveys to its community-based environmental monitoring program (Norris and D'Amore, 1996; Norris and Hutley, 1997). This comprehensive monitoring program integrates scientific data collection with environmental education and includes beach observations, conventional water quality monitoring, weather observations, beach seine observations, and annual demersal fish abundance surveys. The objective of the UV eelgrass surveys is to map and estimate basal area coverage of eelgrass along a one mile section of the Port Townsend waterfront. We define "basal area coverage" to be the number of square meters of the seabed that is occupied by eelgrass. Field maps showing the approximate eelgrass distribution have been produced for each survey, but prior to this study no basal area coverage estimates had been prepared.

Norris et al. (1997) described a technique for estimating basal area coverage from a single UV survey. Their technique collects georeferenced observations of the seabed by integrating UV images with continuously updated (every 2 sec) global positioning system (GPS) data. Images are collected along straight line transects conducted in a grid pattern throughout a study area, and the first and last seagrass observations on each transect are used to delineate the perimeter of the occupied seagrass habitat. The resulting irregular polygon is defined to be the sample region and its area in m^2 is computed using analytic geometry. To account for seagrass patchiness within the sample region, each UV transect is further analyzed to compute its length within the sample region and the length during which seagrass was visible. This sampling scheme is identical to cluster sampling with unequal cluster sizes (each transect is considered to be a cluster of samples) from which a point estimate and approximate 95% confidence interval for seagrass basal area can be computed. When applying this technique in a monitoring context (i.e., multiple surveys over time), Norris et al. (1997) recommend defining a "global" sampling region from the first and last seagrass observations from all surveys.

The study reported here has three goals. First, we test the applicability of the Norris et al. (1997) technique in a monitoring context, focusing on the problem of defining a global sampling region and its

effect on sample estimates. Second, we estimate the four-year trend in eelgrass basal area coverage in one location along the Port Townsend waterfront. Third, we examine differences in basal area coverage between summer and winter surveys.

Methods

Study Site

Each four-day UV survey collected data from a one-mile section of waterfront between Point Hudson and the Port Townsend Boat Haven. Figure 1 shows the field map of eelgrass distribution prepared from the September 1997 survey. We computed basal area coverage estimates only for the section nearest the Port Townsend Boat Haven. This site covers approximately 190 m of shoreline and includes about 17 acres between MLLW and the 10-m depth contour. We selected this section because it is the largest continuous eelgrass bed in the study area and the Port of Port Townsend is considering expanding the Port Townsend Boat Haven.

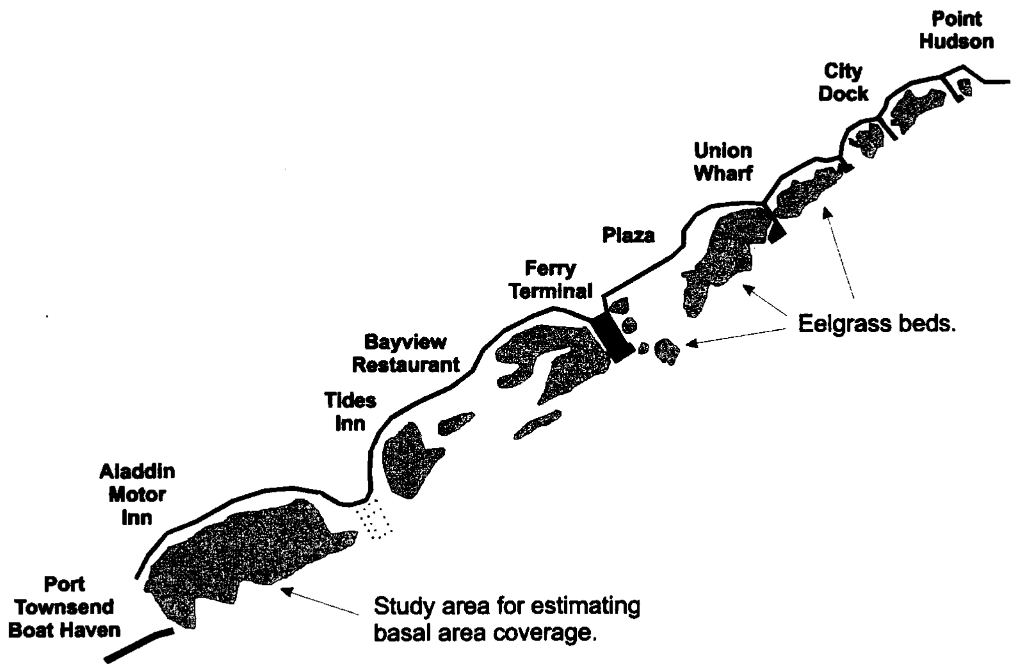

Figure 1. Eelgrass distribution along a one-mile section of the Port Townsend waterfront prepared from the real-time mapping data collected during the September '97 survey. All basal area coverage estimates were determined for the eelgrass bed just northeast of the Port Townsend Boat Haven.

Underwater Videographic Mapping System Overview

The mapping system was composed of two components—a real-time mapping system and an underwater videographic system (Figure 2). The real-time mapping system created preliminary thematic maps during the data collection process in the field. These maps were helpful for adjusting field sampling plans. Data collected by the underwater videographic system were post-processed and analyzed in the laboratory to estimate basal area coverage.

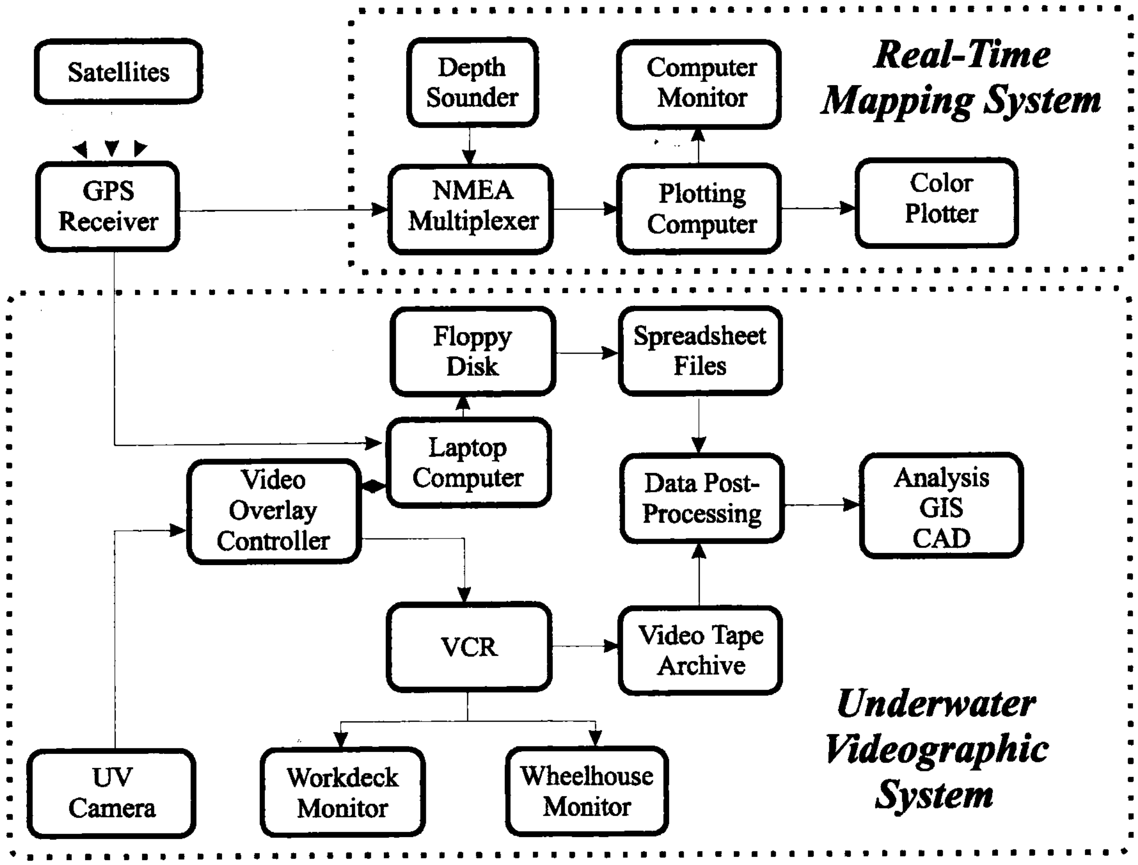

Figure 2. Schematic diagram of the underwater videographic mapping system used in this study.

Survey Equipment

The system was deployed aboard the 11-m commercial fishing/research vessel *Brendan D II*. For six of the eight surveys, position data (latitude and longitude) were acquired by differential GPS (DGPS) from the United States Coast Guard public DGPS network. DGPS was not available for the first two surveys. The GPS antenna was located at the tip of the cargo boom used to deploy the camera. Underwater video images were obtained using an underwater camera mounted in a "down-looking" orientation on a heavy towfish. A 250-watt underwater light provided illumination. The towfish was deployed directly off the stern of the vessel using the cargo boom and boom winch. The heavy weight of the towfish helped keep the camera positioned directly beneath the DGPS antenna. A laptop computer equipped with a video overlay controller and data logger software integrated DGPS data (date, time, latitude, longitude) and the video signal. DGPS data (updated every 2 sec) and transect identification numbers were stored directly onto the videotape using a four head video cassette recorder (VCR). Date, time and position also were stored on a floppy disk at two-second intervals. Television monitors located in both the pilothouse and the work deck assisted the helmsman and winch operator control the speed and vertical position of the towfish.

Field Sampling Procedures

We used a systematic sampling plan composed of straight line transects both parallel and perpendicular to the shoreline. At the start of each transect, the vessel was backed close to the shoreline or dock and the camera was lowered to just above the bottom. Visual references are noted and the VCR and data logger were started. As the vessel moved along the transect the winch operator raised and lowered the

camera towfish to follow the seabed contour. The field of view changed with the height above the bottom, but averaged about one square meter. The vessel speed was held as constant as possible (about one m/sec) so that time could be used as a proxy for distance in some analyses. A tension line from the deck winch was used to help keep the towfish cable in a vertical orientation. At the end of the transect, the VCR was stopped, the camera was retrieved, and the vessel was moved to the next sampling position.

Real-Time Mapping

The real-time mapping system input DGPS position data directly into a spreadsheet program. Position data were added to three data series that were plotted on a chart embedded in the spreadsheet, each series plotted using a different pattern. Virtual toggles or buttons, also embedded in the spreadsheet, controlled which data series were updated with each position update (Figure 3). The first series consisted of only one point—the current longitude and latitude. Each of the remaining two plotting series consisted of longitude and latitude coordinates for the vessel track line when eelgrass was present or absent. These series were updated only if the "tracking" or "eelgrass" toggles were turned on, respectively. The "eelgrass absent" series was plotted as a thin black line, whereas the "eelgrass present" series was plotted as a thick green line. As the vessel moved along the track line, an observer watched the TV monitor and clicked the eelgrass toggle on or off each time eelgrass appeared or disappeared. The result was a real-time plot of the area sampled and where eelgrass was observed.

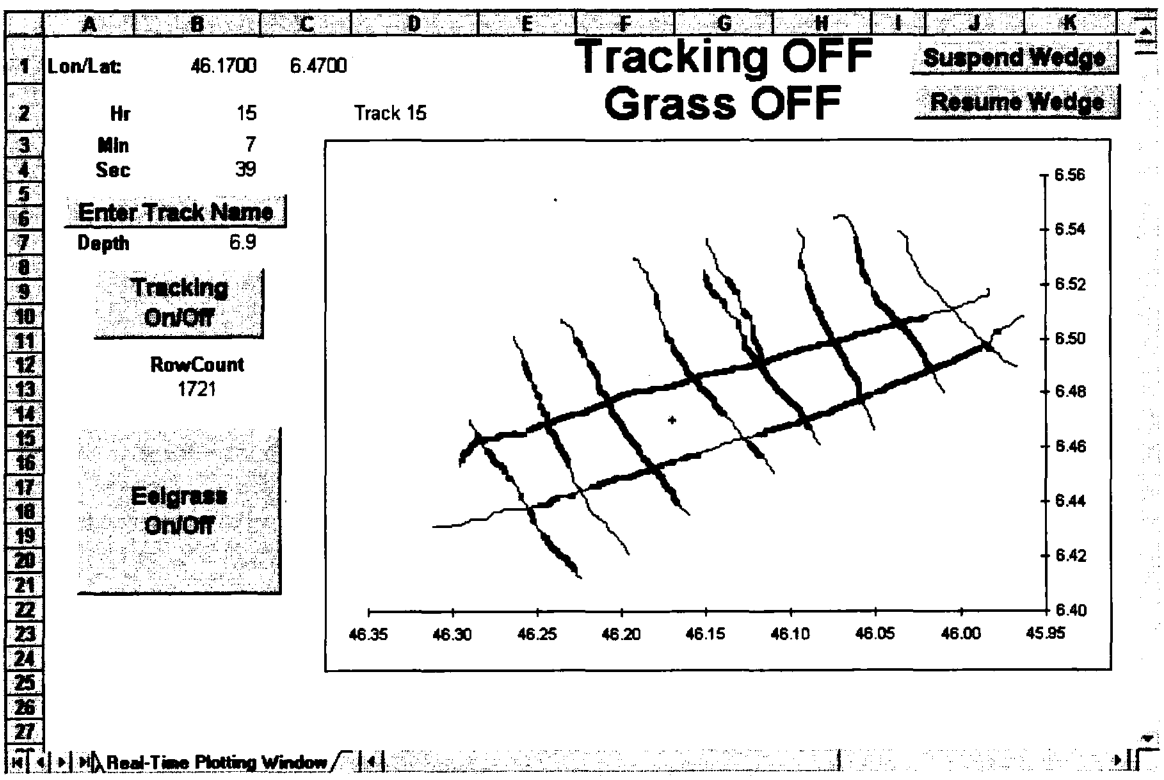

Figure 3. Sample computer screen window for the real-time mapping system. The square marker with cross-hair indicates the current vessel position. When the "Tracking On/Off" button is clicked by the observer to note that the camera is viewing the seabed, a thin line is plotted as the vessel moves along the transect. When the "Eelgrass On/Off" button is clicked by the observer to note the presence of eelgrass on the video monitor, the plot line changes to a thicker line (plotted in green on a color monitor).

Underwater Video Data Post-Processing

Data stored on floppy disks were downloaded and organized into spreadsheet files with separate columns for date, time, and position data. A blank column was created for "eelgrass code." Videotapes were reviewed in the laboratory to assign one of five eelgrass codes to each position record: absent (code = 0), low density (code = 1), medium density (code = 2), high density (code = 3), and undetermined (code = 9). The low, medium, and high-density classifications were determined by the subjective judgment of the videotape reviewer.

To define a global perimeter, we first plotted perimeters for each survey (Figure 4). Perimeters for the six surveys using DGPS were nearly identical, and a global perimeter was defined that encompassed all survey perimeters. For statistical analysis, this global perimeter delineated the sample region for these six surveys. The two early surveys that did not use DGPS had quite different perimeters. For these two surveys, each individual survey perimeter was used to define its sample region.

Statistical Analysis

For each survey, individual transects were analyzed using a proprietary software program. The perimeter defining the sample region was plotted along with each transect. A transect was eliminated from basal area coverage analysis if it did not follow a substantially straight path, or did not pass continuously through the study region. (E.g., some transects were aborted midway through the sample region due to technical problems during data collection; other transects were very close and parallel to the eelgrass bed perimeter and meandered in and out of the sample region).

A few transects from the six surveys using DGPS started within, but very close to, the global perimeter defining the nearshore edge of the sample region. This situation was caused by the two to five meter accuracy limits of DGPS and the fact that some transects running perpendicular to the shoreline started less than 5 m inshore from the nearshore edge of the eelgrass bed. For these transects, the analysis program added to the total length and eelgrass absent component of the transect the distance between the start of the transect and the global perimeter.

For each accepted transect, the program computed the length of the transect passing through the sample region and the lengths associated with each eelgrass code. Once all transects for a survey were analyzed, the following procedures were used to compute basal area coverage estimates and confidence intervals.

Let n be the number of random samples (transects) through a sample region and for the i^{th} transect let m_i = length (meters) passing through the sample region and a_i = length (meters) with seagrass. The proportion of the study region having eelgrass was estimated by Cochran (1977, eq. 3.31).

$$\hat{p} = \frac{\sum a_i}{\sum m_i} \qquad (1)$$

Cochran (1977) notes that this estimate is "slightly biased, although the bias is seldom likely to be of practical importance." The estimated variance of p is given by Cochran (1977, eq. 3.34).

$$\text{var}(\hat{p}) = \frac{\sum a_i^2 - 2p\sum a_i m_i + p^2 \sum m_i^2}{n(n-1)\overline{m}^2} \qquad (2)$$

where $\overline{m}$ is the mean number of elements in a sample unit (= $\Sigma\, m_i / n$). If the transects are of equal length (i.e., $m_i = m$ for all i), the estimates of p and var(p) are just the sample mean and sample variance of the p_i (= a_i/m). The point estimate and approximate 95% confidence interval for the total number of square meters covered by seagrass (A) is given by:

$$\hat{A} = N(\hat{p} \pm 2\hat{\sigma}_p) \quad (3)$$

where $\hat{\sigma}_p$ is the estimated standard deviation of p.

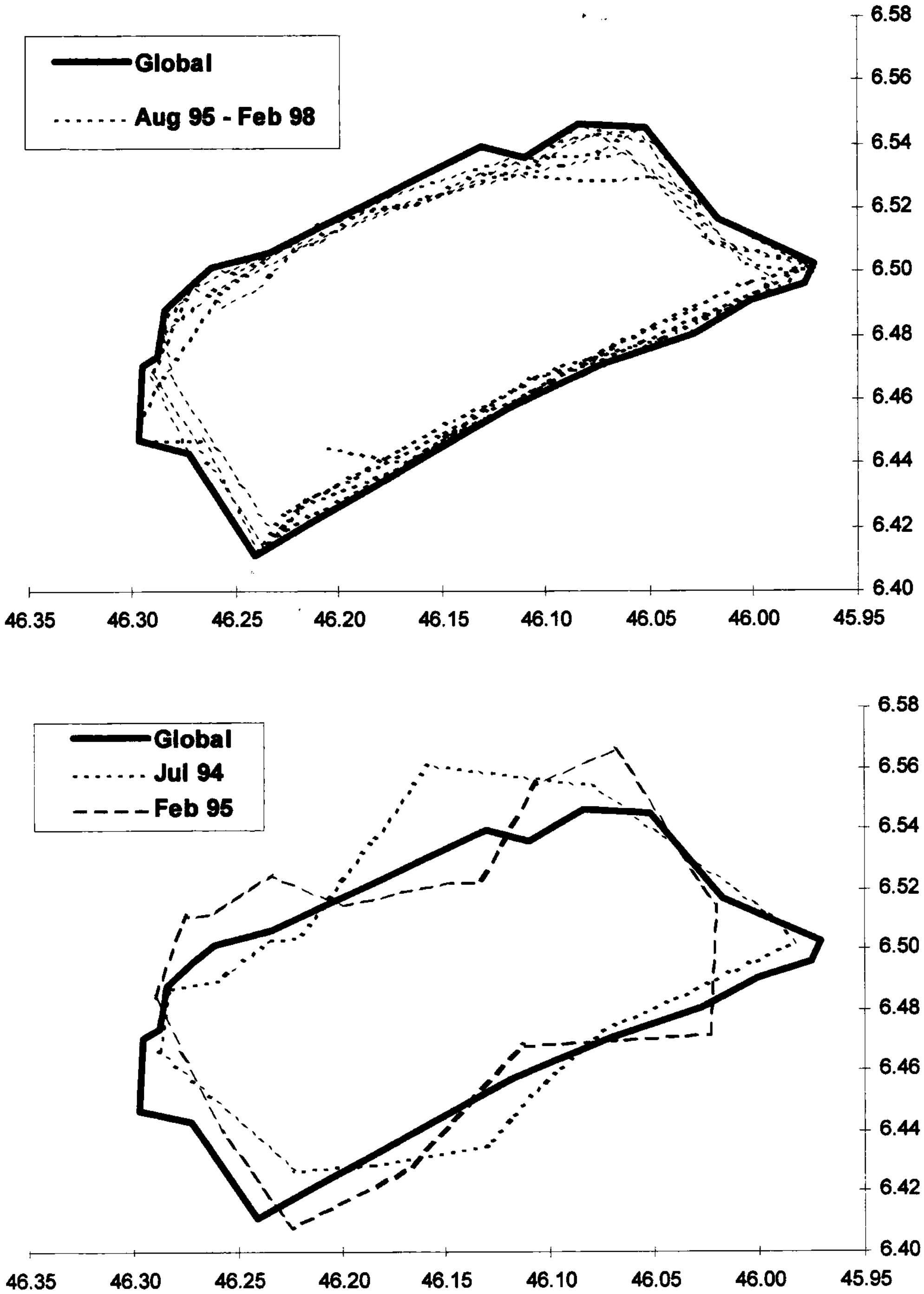

Figure 4. Upper panel (previous page) shows the eelgrass bed perimeters for the six surveys using differential GPS and the "global" perimeter (heaviest black line) used for estimating basal area coverage. Lower panel shows the eelgrass bed perimeters for the two surveys that did not use differential GPS (global perimeter also shown for reference).

Results

A total of 110 transects were included in the analysis (Table 1). The histogram of eelgrass fractions from all transects in all years showed a normal distribution with mean = 0.69 and standard deviation = 0.13 (Figure 5). These values are quite similar to those reported in Norris et al. (1997) for 32 UV transects taken fro m a different Puget Sound eelgrass bed (mean = 0.76; standard deviation = 0.124).

Table 1. Data summary for eight underwater videographic eelgrass surveys in Port Townsend Bay (n = number of transects in the sample region used to estimate basal area coverage). Sample length is the sum of the lengths (in meters) from all n transects passing through the sample region (i.e., Σm_j). Eelgrass lengths for low, medium, and high densities are the sums of the lengths (in meters) from all n transects that have eelgrass of associated density (i.e., Σa_i)

		Sample Length	Eelgrass Lengths (m)				Estimated Eelgrass Fraction $\hat{p}$			
Survey	n	(m)	Low	Med	High	Total	Low	Med	High	Total
Jul-94	13	2,432	116	483	809	1,409	0.05	0.20	0.33	0.58
Feb-95	18	3,453	579	1,021	563	2,164	0.17	0.30	0.16	0.63
Aug-95	14	2,415	196	451	1,004	1,652	0.08	0.19	0.42	0.68
Feb-96	10	1,728	97	380	662	1,138	0.06	0.22	0.38	0.66
Jul-96	14	2,078	92	315	1,057	1,464	0.04	0.15	0.51	0.70
Mar-97	14	2,400	140	1,209	456	1,806	0.06	0.50	0.19	0.75
Sep-97	9	1,856	83	233	1,047	1,363	0.04	0.13	0.56	0.73
Feb-98	18	3,332	175	418	1,895	2,489	0.05	0.13	0.57	0.75

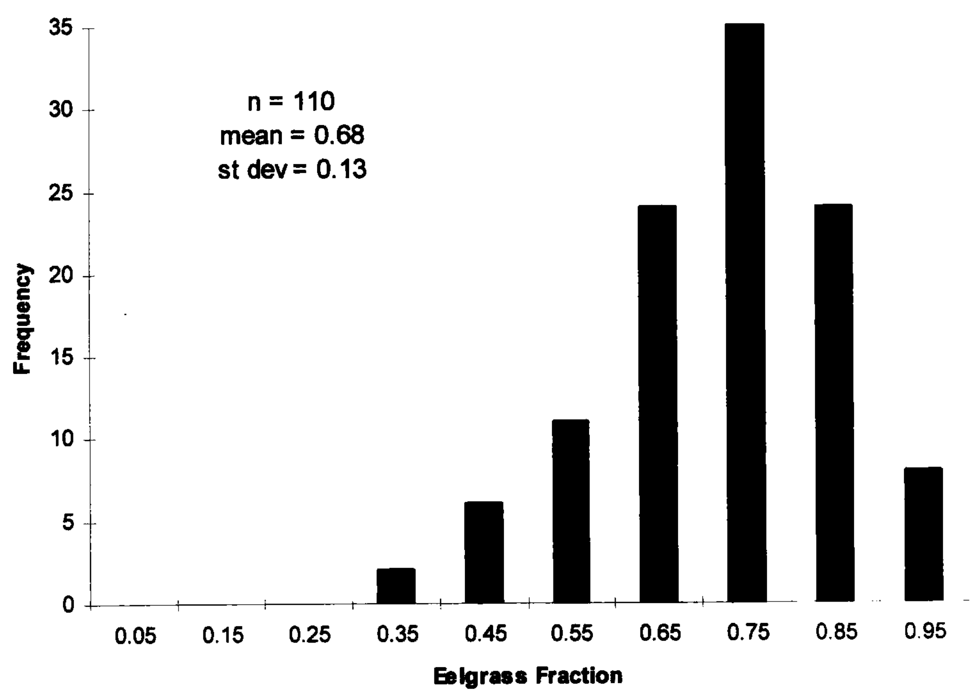

Figure 5. Histogram of total eelgrass fractions collected from 110 UV transects during eight surveys in Port Townsend Bay.

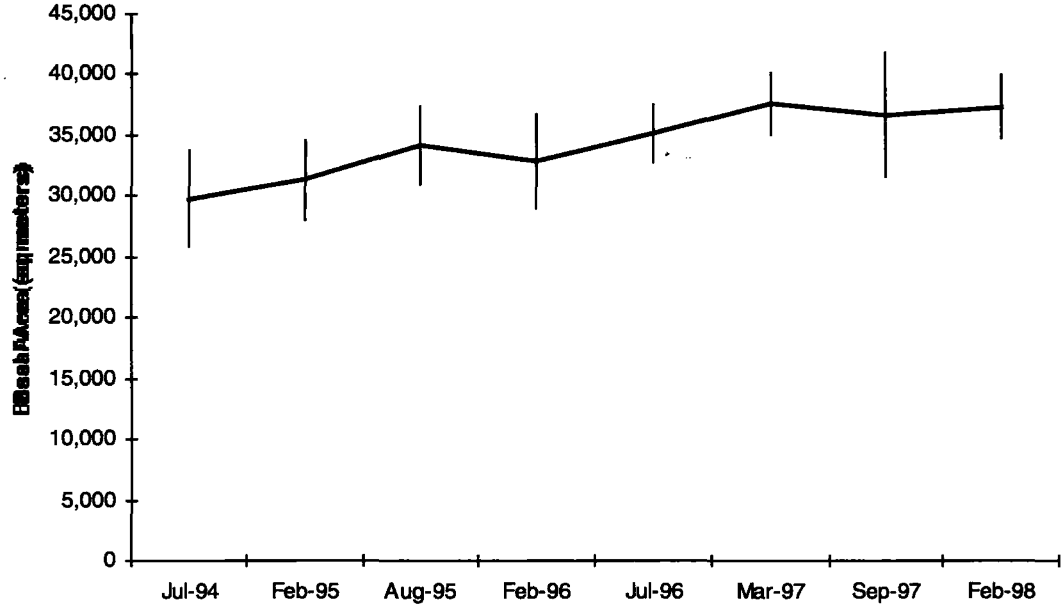

Figure 6. Basal area coverage estimates (with 95% confidence limits) for total eelgrass presence in the sample region.

Overall basal area coverage showed an increasing trend over the four-year period (Table 2; Figure 6). The point estimates for the first (July 1994) and last (February 1998) surveys were 29,808 m^2 and 37,310 m^2, respectively. This is an increase of 7,502 m^2 (25%). The confidence intervals ranged from 7% to 14% around the point estimates.

There were no significant changes in overall basal area coverage between the winter and summer surveys. Also, the low, medium, and high-density eelgrass estimates showed no consistent trends based on our subjective characterization (Table 2).

Discussion

The primary technical difficulty in applying the Norris et al. (1997) method in a monitoring context was that some transects had to be eliminated or adjusted to meet the statistical analysis criteria. This difficulty can be removed by defining the global perimeter of the sample region before field sampling and having the global perimeter plotted on the real-time mapping screen during field sampling. This will ensure that all transects pass completely and continuously through the sample region.

The confidence intervals around the point estimates were not as narrow as we would have liked. As expected, the confidence limits were generally narrower when sample sizes (i.e., number of transects) were larger. To estimate how many transects would be needed to reduce the 95% confidence intervals to within 5% of the point estimate (i.e., coefficient of variation = 0.025), we can assume all transects have the same length and use the standard deviation of the eelgrass fractions from all 110 transects ($\hat{\sigma}_p$) as follows:

$$\hat{n} = \frac{\hat{\sigma}_p^{\,2}}{(0.025)^2}$$

Table 2. Basal area coverage estimates (m^2) with upper and lower 95% confidence bounds for low, medium, and high density eelgrass and total eelgrass presence from eight underwater videographic surveys in Port Townsend Bay.

Survey Date	Eelgrass Density	Lower Bound	Point Estimate	Upper Bound
Jul-94	low	1,491	2,458	3,426
	med	7,455	10,229	13,003
	high	13,209	17,121	21,032
	total	25,733	29,808	33,884
Feb-95	low	6,100	8,390	10,681
	med	12,297	14,791	17,285
	high	4,756	8,159	11,562
	total	27,982	31,341	34,700
Aug-95	low	2,272	4,053	5,835
	med	6,923	9,334	11,744
	high	15,352	20,776	26,200
	total	30,827	34,163	37,499
Feb-96	low	1,786	2,798	3,810
	med	8,801	10,974	13,148
	high	15,180	19,124	23,069
	total	28,926	32,896	36,866
Jul-96	low	1,387	2,216	3,046
	med	5,589	7,581	9,573
	high	21,521	25,395	29,270
	total	32,711	35,193	37,675
Mar-97	low	2,129	2,916	3,704
	med	20,135	25,177	30,220
	high	3,662	9,496	15,329
	total	34,937	37,590	40,243
Sep-97	low	743	2,227	3,712
	med	3,620	6,272	8,923
	high	21,159	28,170	35,181
	total	31,470	36,669	41,868
Feb-98	low	1,976	2,629	3,282
	med	4,138	6,267	8,397
	high	23,711	28,414	33,116
	total	34,616	37,310	40,005

Substituting $\hat{\sigma}_p = 0.13$ (from Figure 5) gives an estimated sample size of 27 transects. The similarity in eelgrass fraction standard deviations (0.13 vs. 0.12) between transects from this study and that reported in Norris et al. (1997) suggests that a good rule of thumb is that 25 to 30 UV transects are required through a typical Puget Sound eelgrass bed in order to estimate basal area coverage within 5%. It is important to note that the required sample size is independent of the size of the bed. The critical characteristic is how patchily the eelgrass is distributed within the bed perimeter.

Our finding that basal area coverage did not change significantly between winter and summer suggests that the current WDFW policy requiring eelgrass surveys to be conducted only during the summer may be relaxed, depending on the purpose of the survey. If the perimeter of an eelgrass bed and

associated basal area coverage are the only parameters of interest, our results suggest that surveys conducted at any time of year will provide the same information. For the Port Townsend Marine Science Center monitoring program we recommend eliminating the winter survey each year and adding two other sites to the summer surveys—near the mouth of Chimacum Creek and near known herring spawning areas inside Kilisut Harbor.

The fact that we observed a 25% increase in basal area coverage over the four year period also has implications for the WDFW "no net loss" policy. In absolute terms, the observed increase was about 7,500 m^2. This is a significant amount of eelgrass that could easily represent the amount of eelgrass impacted by a nearby construction project. From a policy application perspective, the critical question is: "During what two time periods does a 'no net loss' policy apply?" For example, if the policy for our study region begins in July 1994 (the date of our first survey), the eelgrass bed existing in February 1998 could be reduced by 7,500 m^2 and still satisfy the policy. In more general terms, the question is: Should a construction project that will destroy some eelgrass habitat be allowed to proceed, if it is known that the eelgrass bed in the immediate vicinity has increased naturally by the same or greater amount during the past few years?

In summary, we feel that the UV methodology described here and in Norris et al. (1997) satisfies all of the requirements for an eelgrass monitoring program outlined in the introduction. One day of field sampling effort (25-30 UV transects) at each time period provides statistically valid basal area coverage estimates capable of detecting a 5% change between time periods. This method complements other larger scale remote sensing techniques, such as satellite imagery and aerial photography.

Acknowledgments

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Long-Term Monitoring of the Navy's Manchester Eelgrass Bed

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Introduction

The Navy's Manchester Fuel Depot (MFD), located at Orchard Point in southern Kitsap County, has supplied petroleum products to military vessels since World War II. Because of the generally poor condition and outmoded design of the MFD fuel pier, it was replaced with a new pier of comparable length. The replacement project involved dredging about 80,000 m^3 of material from the site of the new pier, constructing a new 390-m fuel pier, and removing the old pier. Pier replacement began in February 1991 and was completed in March 1993. Further details of the project are provided in Roni and Weitkamp (1996).

We began a monitoring program in 1991 to assess environmental conditions before, during, and after the pier's replacement. Monitoring included monthly water quality sampling (pH, temperature, salinity, turbidity, and dissolved oxygen) at stations around the pier, annual measurements of the distribution and density of eelgrass (*Zostera marina*) adjacent to the pier, and determination of nearshore fish community structure and abundance by beach seining on both sides of the pier at weekly or biweekly intervals during the period of expected chum salmon outmigration (mid-late March through mid June). Chum salmon were the focus of the fish study because of concerns that the pier replacement might affect their along-shore outmigration. Although water-quality measurements and beach seining were stopped when the monitoring project was completed in 1993, we have continued to monitor the eelgrass distribution and density each year since then, except in 1995.

This project has provided us with a unique opportunity to monitor closely a Puget Sound eelgrass bed and its associated fish community over several consecutive years. The changes and degree of interannual variability we observed far exceeded our expectations and would not have been obvious had we monitored for only one or two years, the typical length of similar monitoring projects. Because ecosystems are not often examined in ways that allow us to observe the natural range of variability, we often underestimate the variability of ecosystems. Consequently, in light of this uncertainty, caution should be used when basing long-term management decisions on short-term observations.

Results

Water Quality

Water-quality conditions, measured between 1991 and 1994 during pier replacement, were largely unaffected by pier construction. Typically, water qualities at sampling stations around the pier were no different from those at a control station about two km away. On several occasions turbidity increased slightly during active dredging, but the increase was restricted to the sampling station closest to the dredging and was apparently short-lived. As expected, water temperatures become colder in winter and warmer in summer. In 1992, water temperatures were several degrees warmer than in other years, presumably due to regional warming by the El Niño.

Eelgrass

As the new fuel pier was constructed and the old pier removed between 1991 and 1993, the distribution of eelgrass around the piers varied each year (Figure 1). Since 1993, when the pier replacement project was completed, the distribution of the eelgrass bed had gradually increased around the pier and spread seaward (Figure 1). In addition, several small patches of eelgrass observed in 1991–93 west of the pier were not all seen in 1994 or 1996 but reappeared in 1997.

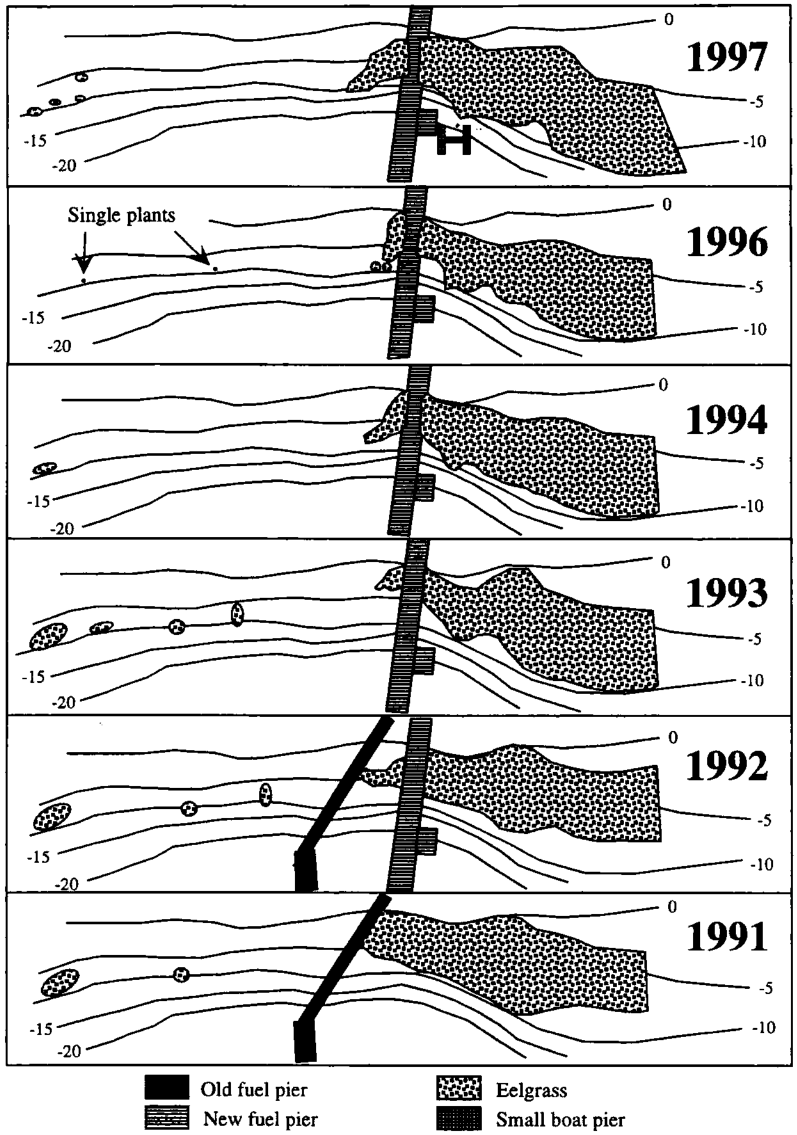

Figure 1. Approximate distribution of eelgrass near the Navy Fuel Piers, Manchester, Washington. The presence of old and new fuel piers during each survey is indicated. Contour lines are in feet below mean lower low water.

Table 1. Densities of reproductive and vegetative shoot densities from the large eelgrass bed directly east of the Navy's new Manchester fuel pier. NA = not available.

Year	Reproductive Shoots/m^2 (s.d.)	Vegetative Shoots/m^2 (s.d.)
1991	14.9 (5.0)	NA
1992	12.3 (8.1)	NA
1993	2.1 (3.2)	124 (NA)
1994	2.1 (2.4)	524 (251.9)
1996	4.6 (4.9)	402 (254.1)
1997	12.9 (9.7)	319 (164.9)

Densities of both vegetative and reproductive eelgrass shoots along transects east of the pier have also exhibited considerable interannual variability (Table 1). Reproductive shoots were abundant, exceeding 12 shoots/m^2 during 1991, 1992, and 1997, and largely absent (<5 shoots/m^2) in the intervening years. Vegetative shoot densities peaked in 1994 and have been declining since then (Table 1).

Nearshore Fish Community Composition and Abundance

During the three years of monitoring the nearshore fish community (1991–1993), 42 fish species were recorded, representing 17 families, including 10 species of Cottidae (sculpins), six species of Pleuronectidae (flatfishes), and five species of Salmonidae. Most fish identified were typical of Puget Sound intertidal beaches (Miller et al. 1975; Wingert and Miller 1979; Borton 1982). Some of the more unusual species caught included big skate (*Raja binoculata*), grunt sculpin (*Rhamphocottus richardsoni*), and tidepool snailfish (*Liparis florae*).

The number of fish species recorded and their seasonal abundance showed considerable interannual variation (Figure 2). For example, in 1993 very few fish (<400 fish/ha) representing only a few species were caught in beach seines between mid-late March and mid-May, while catches during that same period in 1991 and 1992 averaged 1,000–2,500 fish/ha and included almost twice as many species. From mid-May through mid-June, however, the situation switched, and in 1993 the numbers of fish and species caught exceeded that in 1991 and 1992.

The abundance and timing of juvenile chum salmon exhibited even more marked contrasts among years (Figure 2). The timing of peak juvenile chum salmon densities in 1992 occurred two months earlier than it did in 1993, while the peak abundance of chum salmon in 1993 was almost three times that in 1991.

Discussion

Whether the observed variation in the eelgrass bed and associated fish community was caused by the pier replacement project, by other factors such as environmental variation, or by some combination of the two is unclear. This is due to the lack of a consistent control site unaffected by pier construction, as well as possible undetected effects of the new pier on the nearshore environment. However, it is likely that some of the observed variability would be independent of pier effects while some may have been influenced, in part, by pier replacement.

Eelgrass beds naturally display considerable interannual variation in perimeter shape and position (Spratt 1989). Consequently, some of the distributional changes observed during monitoring are likely to reflect natural variation. Shading by barges (brought in to serve as work platforms for dredging and pile driving) and decreased water clarity during dredging may also have affected the eelgrass, particularly in areas of high disturbance. Since the project was completed in 1993, however, the position and shape of the eelgrass bed has continued to change. This continued change might be due to high natural variation independent of the pier replacement, continued effects of the new pier, or other factors. For example, the new pier appears to allow considerably more along-shore flow than did the old pier, and eelgrass is sensitive to currents (Fonseca et al. 1983, Phillips 1984). Although the source of this continued change is unknown, each year the boundary of the eelgrass bed continues to move several meters and small patches of eelgrass appear and disappear.

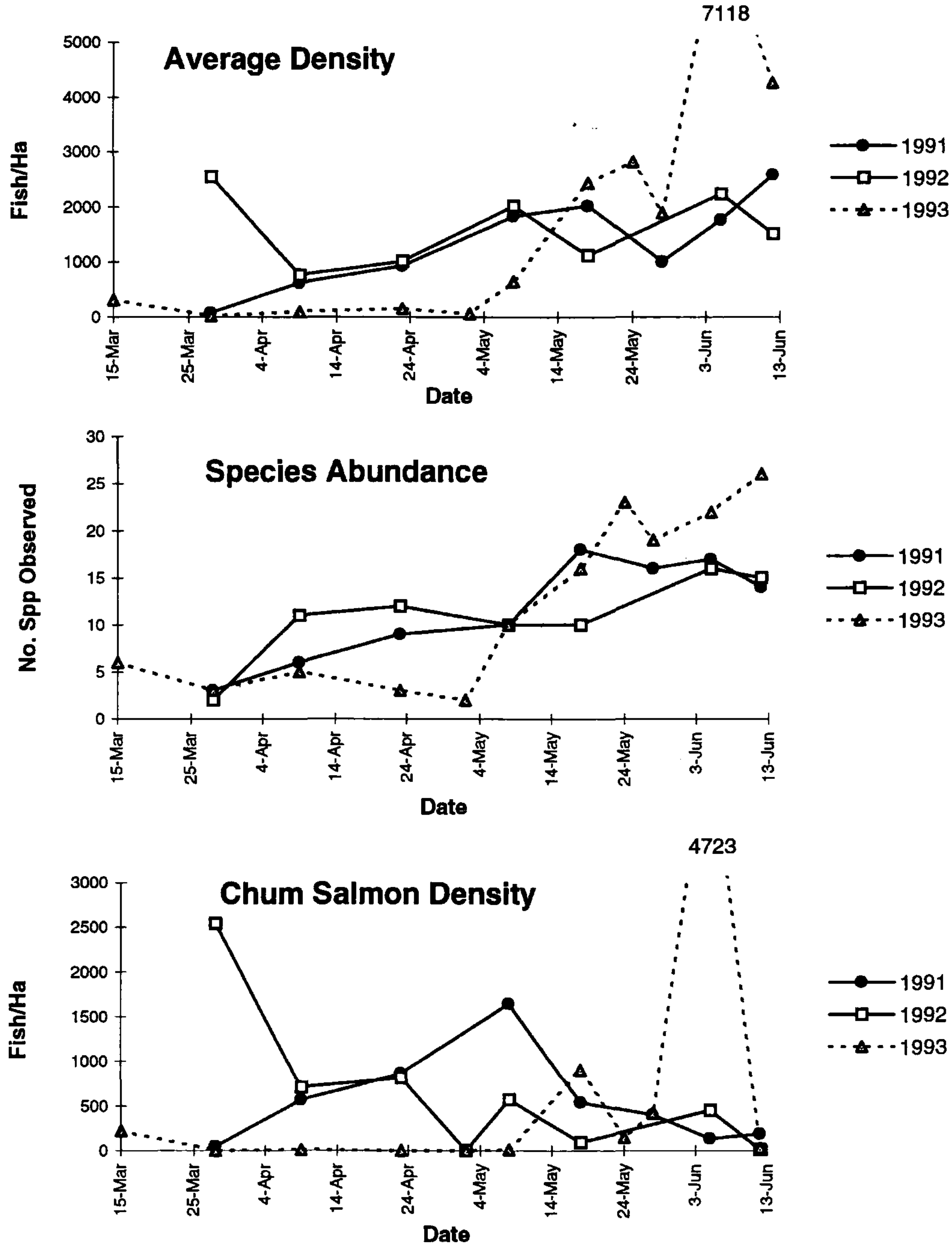

Figure 2. Results of beach seining at the Navy's Manchester fuel pier during spring 1991, 1992, and 1993: average density of all fish (top), total number of species identified (middle), and average density of chum salmon (bottom). The new pier was being built during 1991 and 1992, while seining in 1993 occurred after the old pier was removed and the project was completed.

Reproductive shoot densities recorded in the large eelgrass bed in 1993–96 (2–5 shoots/m^2) were much lower those measured in 1991, 1992, or 1997 (12–15 shoots/m^2), and lower than is typical for Puget Sound (6–66 shoots/m^2) (Phillips 1984) or Manchester eelgrass (5–9 shoots/m^2) (Phillips et al. 1983). Although this decline might be expected from the disturbance of pier replacement, it appears that at least the 1993 changes were independent of it. The production of reproductive shoots depends on numerous environmental parameters, including ambient light levels and temperature (Keddy 1987; Phillips et al. 1983; van Dijk et al. 1992), both of which are affected by weather. The spring of 1993 was one of the wettest and cloudiest on record in the Puget Sound region (WCIS 1998). In addition, reproductive shoot densities at two other eelgrass beds in Central Puget Sound were also low in 1993. This suggests that low reproductive shoot densities in 1993 were regional in scope and may have been influenced by the cool, wet weather rather than site-specific environmental disturbance due to pier replacement.

Comparisons of fish catches in 1991, 1992, and 1993 indicate that the greatest differences among years were found in the timings and magnitudes of peak densities and species richness. In contrast, average values for fish densities and species richness over this period were fairly similar. Fish, like other ectotherms, are temperature-sensitive and therefore differences in timing between years probably resulted primarily from natural variability in water temperature and weather rather than from anthropogenic factors associated with pier replacement. The magnitudes of peak densities and species richness, however, may have resulted from both anthropogenic and natural factors. For example, chum salmon have been observed to avoid pier construction sites (Bax et al. 1980) or in-water construction (Feist 1991), while tide stage strongly affects beach seine catches (Bax 1983; Borton 1982). In addition, water temperature may affect larval fish mortality, thereby influencing densities of juvenile fishes.

Consequently, exceptionally warm water temperatures in 1992 may explain the earlier timing of events in 1992 compared to 1991 or 1993. In contrast, the exceptionally high fish densities and species richness observed in 1993 may partially reflect improved environmental conditions around the fuel pier. Additional monitoring would be required to distinguish between natural variation in fish densities and species richness and improved environmental conditions associated with the new fuel pier.

Regardless of its source, the variability observed in the Manchester eelgrass bed and associated nearshore fish community greatly exceeded our expectations. Although we expected some changes in response to the pier replacement, we anticipated neither the magnitude of the interannual variability—such as the timing of peak chum salmon abundance—nor the continuing change in eelgrass long after project completion. Although our monitoring occurred during an extreme environmental event, an El Niño, such events are part of the natural variability experienced by Puget Sound ecosystems.

Nearshore communities, like other marine ecosystems, are commonly thought to be largely static entities, with predictable, seasonal changes. Our study, like previous studies examining interannual variability in eelgrass (Orth and Moore 1984; Spratt 1989; Olesen and Sand-Jensen 1994) and other macrophyte (e.g., Dayton and Tegner 1984) communities, reminds us that this is not necessarily the case—eelgrass patches may come and go, may change position or density, and their associated fish communities may be quite different from year to year. Consequently, what we observe one year may or may not hold true in subsequent years. Given this potentially high variability, it is especially important to use caution when basing long-term management decision on short-term observations. Ecosystems may not function or behave as expected when we base our expectations on a mere "snapshot" of a constantly changing entity.

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Chlorin Accumulation as a Proxy for Changes in Past Productivity in Annually Laminated Sediments of Saanich Inlet

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Introduction

The ability to predict the future behavior of the ocean as a sink for fossil fuel CO_2 rests on our understanding of phytoplankton productivity in today's ocean as well as past changes in ocean production. Since the anthropogenic increase of atmospheric carbon dioxide is expected to result in substantial warming of the earth's surface (Houghton and others, 1996), understanding the interactions between climate and carbon cycling has become of considerable public and scientific interest.

The chlorophyll concentration in seawater is commonly used to estimate primary productivity in the ocean. The accumulation of chlorins, transformation products of chlorophyll, recorded in ocean sediments has been proposed as a measure for changes in total primary production over glacial-interglacial time scales (Harris et al., 1996). Developing proxies for changes in primary production over shorter time periods is also critical. The effect of interannual and interdecadal variability such as El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) on fisheries recruitment (Ware and Thomson, 1991; Mantua et al., 1997) and climate change (Ware, 1995; Zhang et al., 1996) has been established.

Aside from instrumental records, decadal records of regional climate variability in the Pacific Northwest are limited. In this paper we demonstrate that there is no evidence of degradation of chlorophyll pigments in the top 1.4 m of anoxic sediments from Saanich Inlet. Since these chloropigments are a direct result of overlying productivity, changes in the concentration of these compounds can serve as a record of variations in phytoplankton production.

Experimental

Site Description Saanich Inlet (British Columbia, Canada; Figure 1) is a highly productive fjord characterized by a 75-m sill that limits the renewal of bottom water. This physical isolation combined with the high primary productivity in the fjord results in anoxic conditions at depths below 150m (Richards, 1965). Productivity is largely dominated by a spring diatom bloom (Hobson, 1983; Sancetta and Calvert, 1988) followed by a series of periodic and less intense summer blooms (Takahashi et al., 1977). The composition of settling particles during the summer is dominated by flocs with diatoms, often with intact chloroplasts. During the winter, sinking materials are composed primarily of detrital particles (Sancetta and Calvert, 1988) originating from the Cowichan and the Fraser Rivers outside the fjord (Stucchi and Whitney, 1997).

The absence of macrofauna and the consequent lack of bioturbation in the anoxic sediments leads to the formation of alternating detrital and siliceous layers that represent annual varves. Darker laminations correspond to the input of detrital materials associated with river discharges during the rainy winter period. Light bands are related to the deposition of siliceous diatom frustules during the spring and summer blooms.

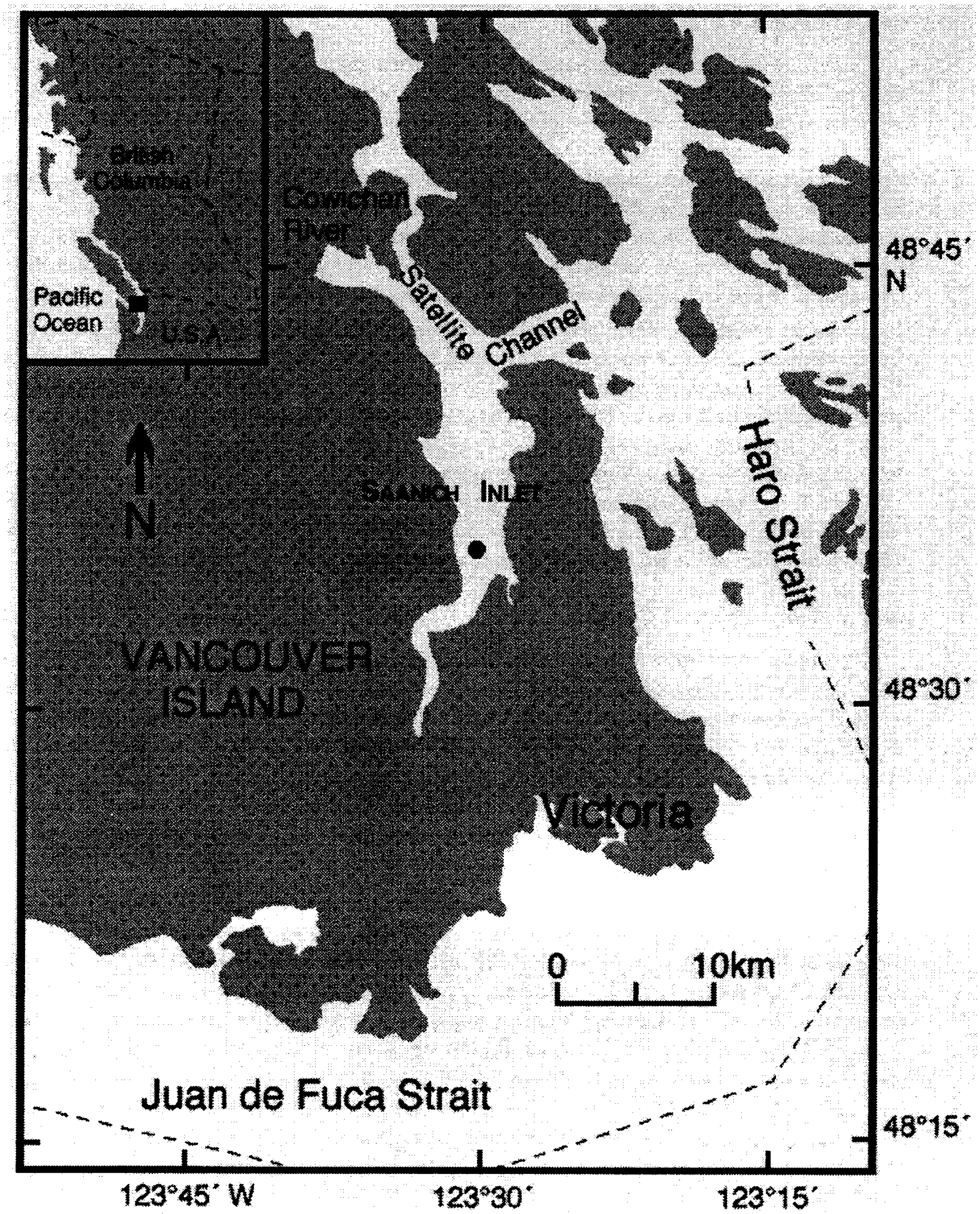

Figure 1. Study area, Saanich Inlet, British Columbia. Dot indicates sampling site at 48°35.1′N, 123°29.5′W.

Sample Collection

Saanich sediments have a high water content, are extremely unconsolidated ("soupy"), and contain methane. These characteristics make collecting sediment cores with intact annual laminations difficult or impossible using conventional techniques such as box coring or gravity coring. For this study we used a freeze-core technique (Shapiro, 1958) modified by Crusius and Anderson (1991). A rectangular aluminum tube filled with a mixture of dry ice and ethanol was inserted into the sediment and left for 20 minutes. The corer freezes the sediment *in situ* prior the retrieval of the corer so that the sediment can be easily retrieved with its laminated structure preserved. We obtained a 145-cm frozen sediment core overlain by frozen seawater indicating that the sediment-water interface was obtained. X-radiographs of the core indicated a laminated structure that corresponded to interbedded bands with high and low detrital content.

The core chronology was established by counting the varves on the X-radiographs. Every light-dark couplet was counted as one year, and we assumed that the first dark layer corresponded to winter 1996–97. The 145-cm core represented 157 years, dating from 1997 to 1840. The uncertainty in the counting was estimated to be ±2 years at 100 years. The averaged varve thickness was 0.85 cm ±0.4 cm. Due to sediment compaction, the upper 15 varves showed an uniform decrease in the varve thickness with depth decreasing from 3 to 0.9 cm. Varves corresponding to 1996, 1973, and 1920 were unusually thick (6.1, 2.8, and 5.8 cm, respectively), corresponding to massive layers deposited by subaqueous debris flows (Blais-Stevens et al., 1997). In order to study annual changes in the accumulation of chlorophyll pigments we sampled the sediments at an annual resolution corresponding to each varve.

Sample Extraction and Analysis

Wet sediment samples (approximately 3 g) were weighed into glass test tubes, centrifuged and the overlying water was discarded. Pigments were extracted three times with HPLC grade acetone with sonication in a water bath at 4_ C. The sediments were dried at 60_ C overnight to obtain the dry weight and percent water. The combined solvent extracts were evaporated under an N_2 stream to a final volume of 4 ml. To purify the extract, 2 ml of 10% aqueous NaCl were added and the resulting mixture was extracted with HPLC grade ethyl acetate until complete decoloration. Samples were dried with anhydrous Na_2SO_4, and the solvent evaporated under an N_2 stream. Extracts were redissolved in 4 ml of HPLC grade acetone for instrumental analysis.

A Waters 510 liquid chromatograph equipped with an automatic injector (Waters 717+) and a photodiode array detector (190–700 nm, Waters 996) was used to separate and identify individual compounds. The detector was operated at 665 and 410 nm for selective monitoring of chlorophyll derivatives. Separation was performed on a C_{18} column (Econosil, 5 µm particle diameter, 250 x 4.6 mm, Alltech Associates Inc.) using a modification of the method described by Zapata (1987). Sample aliquots of 150 µL were mixed with 50 µL 0.5 M ammonium acetate in water prior to analysis. The elution gradient was programmed from 100% solvent A (80% MeOH and 20% of 0.5 M ammonium acetate in water) to 100% solvent B (50% MeOH and 50% acetone) for 20 minutes followed by an isocratic elution for 30 minutes. The solvent flow was 1 ml/min for the first 29 minutes and 2 ml/min for the rest of the analysis.A pigment extract was analyzed by LC-MS and MS-MS for definitive identification of chlorophyll and its derivatives. Each compound was identified as described in Table 1. Additional details of this analysis will be published elsewhere (Villanueva, in preparation).

The extinction coefficient used for the quantification of chlorophylls and its phaeoderivatives are listed in Table 1. A similar molar absorbtion coefficient for all phaeoderivatives is assumed on the basis that they possess the same chromophore ring. The molar absorbance coefficient for chlorophyllide *a* and pyrochlorophyll *a* has been assumed to be the same as chlorophyll *a*. Since pyrophaeophorbide *a* and chlorophyllone coelute, they have been quantified together.

Table 1. Chlorophyll pigments quantified by HPLC in Saanich Inlet sediments.

	Compound	Retention time (min)	Absorbance maxima (nm)	Extinction coefficient[1]	Source[2]
1.	Chlorophyllide *a*	13.8	432/665	100.7 x 10^3	a
2.	Phaeophorbide *a*	18.9	410/665	66.8 x 10^3	a
3.	Phaeophorbide *a'*	19.6	410/665	66.8 x 10^3	
4.	Pyrophaeophorbide *a*	21.5	410/665	66.8 x 10^3	
5a.	Chlorophyllone *a*	21.1	410/665	66.8 x 10^3	
5b.	Chlorophyllone *a*	21.6	409/668	66.8 x 10^3	
6.	Chlorophyll *a*	26.9	433/665	100.7 x 10^3	b
7.	Chlorophyll *a'*	27.3	433/665	100.7 x 10^3	b
8.	Pyrochlorophyll *a'*	27.7	410/665	100.7 x 10^3	c
9.	Phaeophytin *a*	30.1	410/665	66.8 x 10^3	c
10.	Phaeophytin *a'*	30.5	410/665	66.8 x 10^3	c
11.	Pyrophaeophytin *a*	32.3	410/665	66.8 x 10^3	c
12.	Sterylpyrophaeophorbide *a*	35-41	410/665	66.8 x 10^3	

1. Molar extinction coefficient at 665nm (cm^2/M) from Brown (1968). Phaeophytins and phaeophorbides were assumed to have the same molar extinction coefficient.
2. Compounds have been obtained from: a) culture of *Phaeodactylum tricornutum*; b) commercially available; c) synthesized from chlorophyll *a*.

Results and Discussion

Qualitative Analysis

The chromatographic profile obtained from a typical Saanich Inlet sediment sample shows the presence of at least thirteen individual compounds that absorb at 665 nm (Figure 2). The dominant peak in each sample is unaltered chlorophyll *a* (compound 6). The other compounds identified are the result of one or several transformation processes of chlorophyll *a* including (Table 1, Figure 3):

1. the loss of the central Mg atom (compounds 2, 3, 4, 5, 9, 10, 11, 12);
2. the loss of the C_{13} methoxycarbonyl moiety (4, 8, 11, 12);
3. the loss of phytyl moiety (1, 2, 3, 4, 12).

Demetallation of chlorophyll *a* results in the formation of phaeophytins and phaeophorbides. The presence of pyrophaeophorbide *a*, pyrochlorophyll *a*, and pyrophaeophytin *a* are the result of the loss of the C_{13}-COOMe moiety from the non-pyro-homologue. The loss of the phytyl group results in the formation of chlorophyllide *a* and phaeophorbides. Chlorophyllide *a* is usually related to the activity of chlorophyllase, an enzyme contained in diatoms (Jeffrey and Hallegraeff, 1987). These chlorophyll derivatives have been described in senescent algal cultures, phytoplankton blooms, in fecal pellets, in sediment traps, and in surficial sediments. The lack of significant amounts of other derivatives such as mesoderivatives and phorbins (excluding chlorophylls c_1 and c_2) confirms that pigments are at a very early diagenetic stage in this sedimentary environment.

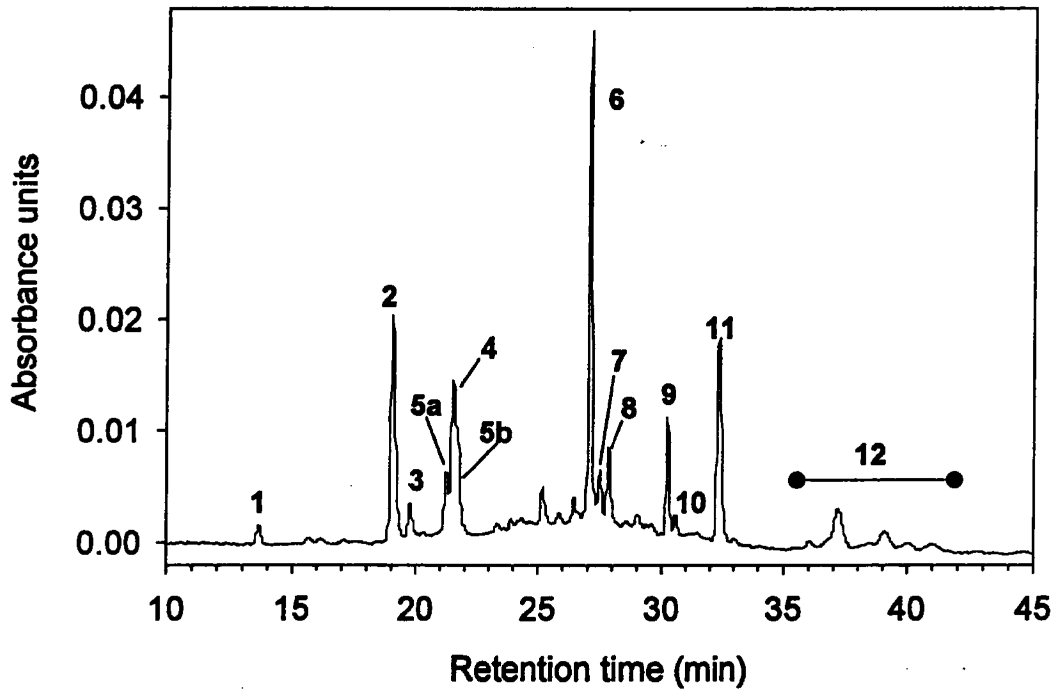

Figure 2. Chromatographic profile obtained from a typical Saanich Inlet sediment.

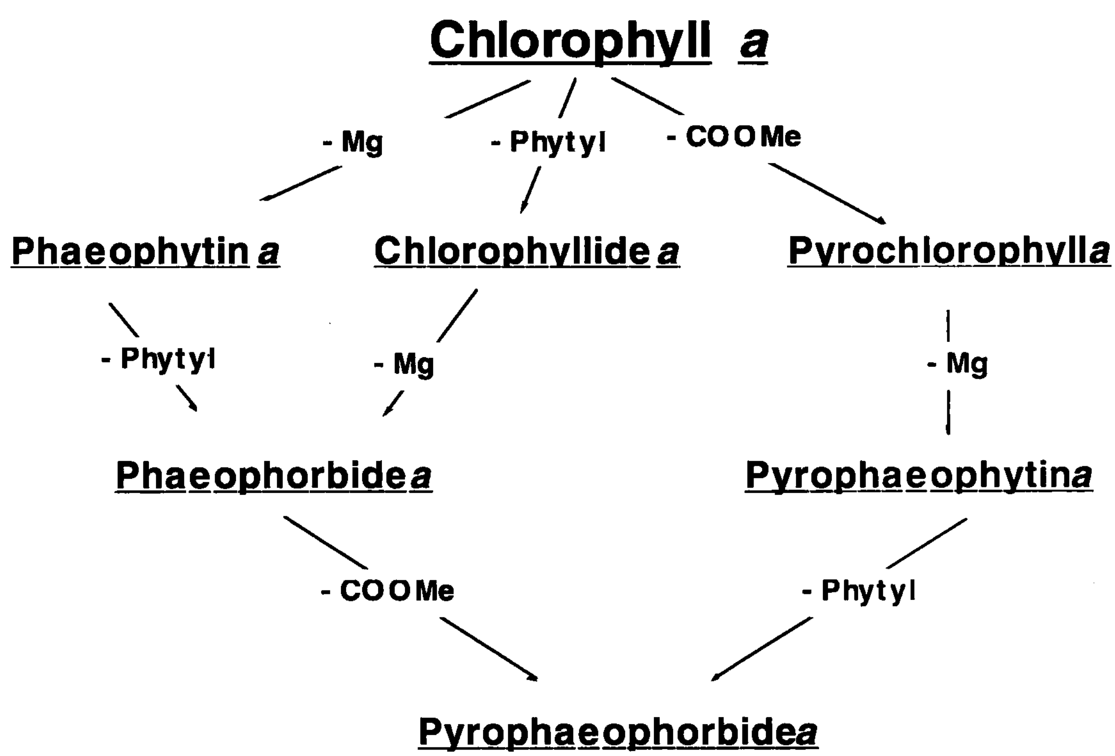

Figure 3. Transformation processes of chlorophyll, and nomenclature for resulting chloropigments.

Quantitative Analysis

The concentration profiles of the 8 major chloropigments present in Saanich Inlet are shown in Figure 4. The main features of these profiles are 1) the lack of a monotonic downcore change in any of the chlorins; and 2) that different compounds have distinct downcore patterns. Given the lability of these compounds in most depositional environments, the lack of a consistent downcore change in any of the chlorins is remarkable.

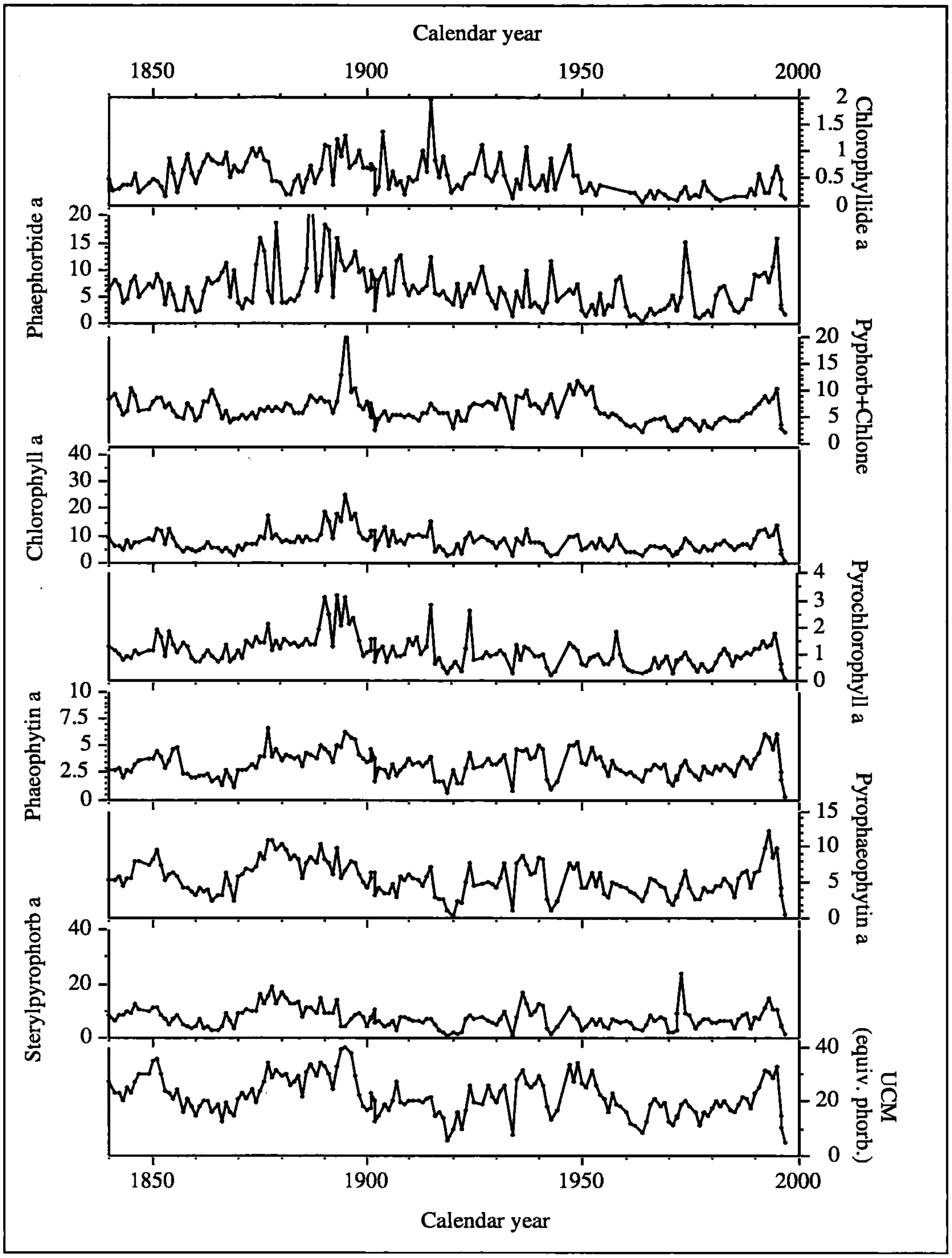

Figure 4. Concentration profiles of chloropigments from annually laminated sediments of Saanich Inlet.

The average composition of samples in the core (Figure 5) offers information on the relative concentration of chlorophyll *a* and its degradation compounds. Chlorophyll *a* represents 20% of the individual compounds detected in Saanich Inlet sediments. The relative contribution of each diagenetic compounds is similar (14–20%) with the exception of chlorophyllide *a* (1%) and pyrochlorophyll *a* (3%) which are the only chlorophyll derivatives that have not undergone demetallation (loss of Mg).

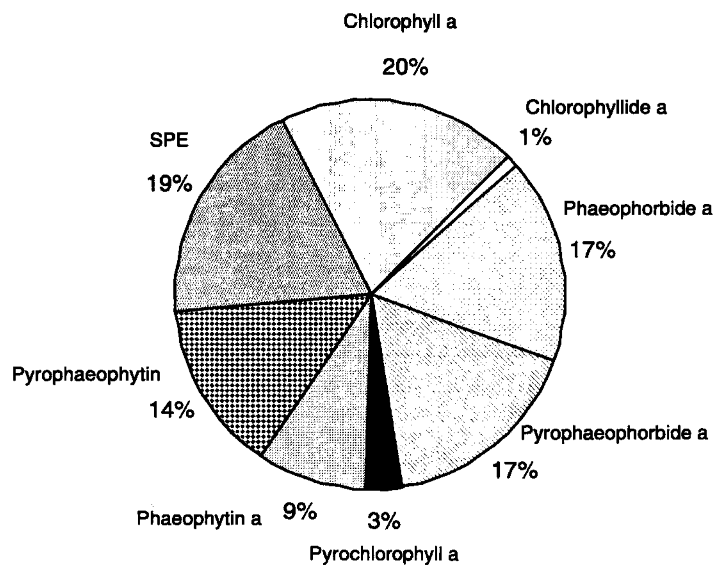

Figure 5. Average composition of chlorophyll pigments in the top 1.4 m of Saanich Inlet sediments.

Downcore Diagenetic Trends

The lack of a consistent downcore trend in individual or total pigments demonstrates that no degradation of chloropigments occurs in the top 1.4 m or 157 years of Saanich Inlet sediments (Figure 4). This feature indicates that processes involving breakdown of the phorbin macrocycle to colorless compounds are not significant in this sedimentary environment over this time interval. The presence of chlorophyll degradation compounds in the sediments is related to processes that take place in the water column, namely respiration in the photic zone and degradation at the sediment-water interface.

As previously mentioned, free chlorophyll *a* undergoes three primary diagenetic reactions: demetallation, loss of the C_{13}-COOMe moiety and hydrolysis of the phytyl chain. In order to estimate the extent to which each of these degradation reactions occur in very early diagenesis, we calculated the percent of total free compounds that have undergone each degradation process. Demetallation appears to be the preferential process, since it involved an average of 75% (±6%) of the total compounds (Figure 6). The remaining 25% include mostly intact chlorophyll *a* as well as minor amounts of chlorophyllide (1%) and pyrochlorophyll *a* (3%). The formation of pyroderivatives includes 53% (±8%) of the individual compounds while the hydrolysis of phytol occurs less extensively and involves only 34% (±11%) of the total compounds extracted from sediments. The lack of a downcore monotonic trend suggests that these reactions occur before incorporation into the sediments.

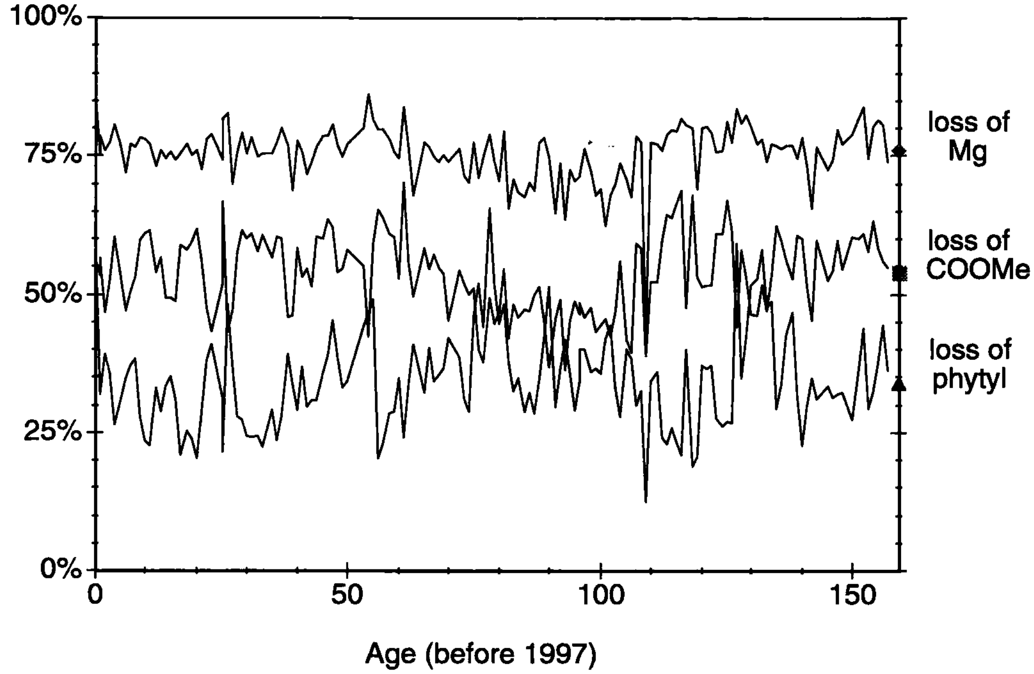

Figure 6. Percent of chloropigments that have lost the central Mg atom (solid line), the methocarboxy moeity (dashed line) and the phytyl group (dotted line).

Total Chlorins as a Productivity Signal

The total chlorin concentration in marine sediments has been proposed as a proxy for changes in marine production over glacial-interglacial time scales (Summerhayes et al., 1995; Harris et al., 1996; Schubert et al., 1998). Assuming that there is no change in the rate or extent of degradation we can infer that differences in the pigment concentration are the result of variations in the annual flux that reaches the sediments. Accordingly, the observed changes in the total amount of sedimentary chlorins can be interpreted in terms of temporal variations in production. The coincidence of the published profiles of total chlorins with other productivity proxies such as opal (Harris et al., 1996), other algal lipids (Summerhayes et al., 1995; Schubert et al., 1998), and total organic carbon (Summerhayes et al., 1995; Harris et al., 1996; Schubert et al., 1998), support these interpretations. Since diagenetic processes do not affect pigment composition within the top 1.4 m of sediments, total chlorins can be used to trace variations in the delivery of chlorophyll to the sediment, that, in principle, are related to changes in algal productivity.

Partial flushing of the anoxic bottom waters with dense, oxygenated water from outside the basin occurs annually in late summer or fall (Anderson and Devol, 1973). Since chlorophyll is especially sensitive to degradation by dissolved oxygen (Hurley and Armstrong, 1991; Leavitt, 1993; Sun et al., 1993a; Sun et al., 1993b), annual variability in chloropigment concentrations could be due to the extent of bottom-water renewal and bottom-water oxygen concentration. We tried to determine whether degradation by O_2 at the sediment-water interface was a primary control of chloropigments by comparing our annual record of sedimentary chlorins with a compilation of more than 275 deep water (>170 m) oxygen profiles dating back to 1953 (Stuchhi, D., Institute of Ocean Sciences, Sidney, B.C., unpublished data). No correlation was found, which supports the argument that changes in overlying production is a primary control.

Possible changes in the "transport efficiency" of pigments through the water column can dominate the fraction of the total chlorins produced in the photic zone that ultimately reach the sediments, and therefore could completely alter the productivity signal. No relationship could be found between the sedimentary chlorophyll concentration and the relative abundance of its derivatives. For example, the extent to which specific degradation reactions occur, such as loss of Mg, formation of pyro derivatives, or

incorporation into the polymeric fraction, has been shown to remain relatively constant from year to year in spite of five-fold changes in the total concentration. Also, the year-to-year variability in the extent of phytol-hydrolysis is not correlated with total chlorins. Although the lack of correlation with bottom-water oxygen and constancy in the pigment composition argues against degradation as a major control of the accumulation of chlorins in the sediment, its possible influence in the productivity signal cannot be ruled out. Any interpretation in terms of productivity should be done with caution.

Spectral analyses of the chlorophyll and total chlorin profiles, based on the maximum entropy method, show similar features that include two prominent peaks at 0.009 (110 yr) and 0.053 (18.9 yr) cycles/yr (Figure 7). Since the pigment record covers a time span of only 157 years, we cannot rely on the statistical significance of the 110-year cycle. The presence of six cycles with a periodicity of 18.9 years is observed in both the chlorophyll and total chlorin profiles.

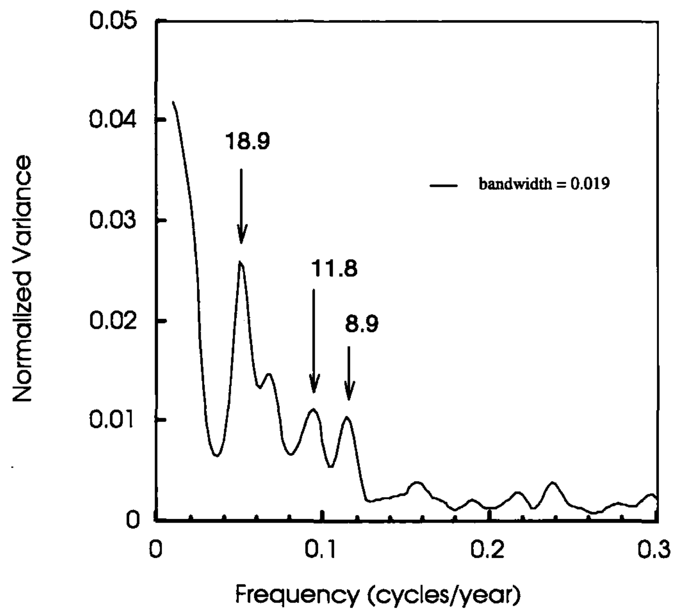

Figure 7. Blackman-Turkey frequency spectrum of the chlorophyll *a* signal in Saanish Inlet sediments over the past 157 years.

Short term (e.g., daily and weekly) changes in production in Saanich Inlet are attributed primarily to the variability in: 1) the tidal mixing outside the mouth of the inlet (Haro Strait) that modulates the input of nutrients to the surface waters of Saanich Inlet; and 2) the stratification of surface waters that favors the development of an algal bloom. Both physical processes are controlled by the spring-neap tidal cycle, giving rise to a biweekly productivity pattern (Parsons et al., 1983; Stucchi and Whitney, 1997). Intensification of tidal mixing results in an increase of the nutrient supply to surface waters, resulting in an intensification of summer blooms. Factors controlling interannual production would include similar processes including tidal mixing (e.g., changes in tidal velocity), fresh water discharge from the Fraser River, density of bottom waters, and insolation. Those factors that are most strongly correlated with changes in the accumulation of chlorins over the past 150 years will be presented elsewhere (Hastings et al., in preparation). The effect of ENSO and the Pacific Decadal Oscillation on each of these factors will allow us to more fully constrain the relationship between climate and productivity in this environment.

Summary

Chlorophyll is produced by all living plants in the marine environment. Accumulation of this pigment and its transformation products in sediments is potentially a useful proxy for oceanic production. Saanich Inlet presents an unique depositional environment to study changes in overlying production and diagenesis of chloropigments because 1) the laminated sediments allow sampling at an annual resolution with high accuracy; 2) bottom-water anoxia substantially limits chlorin degradation; and 3) overlying production is high and variable. Using a freeze corer, we collected 1.4 m (157 years) of annually laminated sediments without disturbance. Average pigment composition indicates that demetallation is the preferential diagenetic reaction since 75% of the compounds have lost the central Mg ion, followed by formation of pyroderivatives (53%) while hydrolysis of phytol occurs less frequently (34%).

No consistent downcore variation was observed in any of the compounds, total chlorins, or the relative fraction of any one compound or class of compounds. This indicates that no degradation of chloropigments occurs over the 157 year time period represented by the core, and suggests that the transformation products are formed in the water column, or at the sediment-water interface. Since diagenetic processes do not appear to affect pigment concentration or composition, total chlorins can be used as a proxy for changes in primary production. Spectral analysis of the chlorin profile indicates a peak at 0.053 cycles/yr or 18.9 years, suggesting that phytoplankton production in Saanich Inlet has a bidecadal periodicity.

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Floating Kelp Resources in the Strait of Juan de Fuca and the Pacific Coast of Washington

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Washington Department of Natural Resources

Bob van Wagonen
Ecoscan Resource Data, Inc.

Abstract

Kelp beds consisting of *Macrocystis integrifolia* (giant kelp) and *Nereocystis luetkeana* (bull kelp) stretch along 313 kilometers (about 12%) of Puget Sound and the Strait of Juan de Fuca. These species have float-like structures that hold the upper portion of the plant at the surface. The multi-canopied beds provide habitat for diverse communities, including critical habitat for many important commercial and sport fishes and invertebrate species, such as juvenile and adult salmon, rockfish, herring, lingcod, abalone, and crab. Since 1988, the Department of Natural Resources, Ecoscan Resource Data, and other agencies have used aerial photography to map floating kelp in the Strait of Juan de Fuca and along the outer coast. Trends in annual areal extent, density, and species composition over nine years are analyzed. Despite interannual fluctuations, the total area of floating kelp beds has not changed significantly over the last five years. However, significant changes may be occurring over longer periods or within smaller areas. These trends will be discussed in the context of water temperatures, nutrients, weather, shoreline processes, and El Niño events.

Role of Community Members in Fight Against Exotics: *Spartina* Watch as a Case Study

Chrys Bertolotto
Adopt-a-Beach

Abstract

In the past four years, Adopt-a-Beach has worked with many partners (governments, tribes, community groups, and schools) to train community members to look for new infestations of *Spartina*, a noxious weed. Over 700 miles have been surveyed by over 250 community members, 30 new infestations have been discovered and removal work has begun or been completed at 18 of those sites.

This paper will address several points:

- The basic premises, and partnership and advisory roles in creating and refining the program;
- The long-term nature both of the threat of exotics and of community stewardship;
- Data management, quality assurance, quality control, and shoreline criteria plans to be outlined to address commonly stated concerns about volunteer monitoring;
- Practical uses, to date, of the data by watershed planners, researchers, land use managers, and community assessment of sensitive sites;
- Discussion of a species-specific program versus multi-species program; and
- The role of communities after major eradication or control efforts have occurred.

The goal of this paper is to outline components of a successful citizen stewardship program directed at stopping the spread of existing exotics so that others may learn about the program and perhaps copy its successes without having to live through the difficulties of trial and error.

2C: Aquatic Plants and Algae

Questions & Answers

Q: (unintelligible question about) the proposed ESA listing for chinook salmon?

A: Since there was a proposed listing of summer chum, and chum salmon do tend to use eelgrass beds, I'd say that's more important.

Q: Does anybody else here have any thoughts on this?

A: I don't know, John, but it seems like the fish might be doing a couple things. First, they might spend time in eelgrass meadows when they're smaller where they're feeding on the zooplankton that are associated with the plants. Then, as they get larger, they may switch to planktonic feeding – though there may be more plankton associated with kelp beds. That would be my guess. There wouldn't be as many as these benthic things, but they'd just be more productive in the kelp beds. Sort of a switch with size or with age.

Norris: I'd like to expand it to include dock structures. One of the things that we did in Port Townsend Bay is that we did the underwater survey for the Union Wharf when they demolished that. On underwater video surveys, we didn't see any fish in the eelgrass, but when we took the camera underneath the dock, it was full of fish. And the contractors, in their process of bidding, looked at the videotape to determine, because one of their requirements was that they had to remove all of the things that they ... they couldn't just cut the dock off and let it sink. They had to haul the stuff away. And they wanted to know what was on the bottom before they started their work. When they looked at the video and saw all of the fish under the dock, one of them called me up and said, hey, maybe we should be leaving this stuff. Maybe an artificial reef is another important component of this habitat as well as the eelgrass. I don't know the answer to that. I'm just a mapper. But that's some of the kinds of comments that we get from the citizen volunteers that come out on the boat.

Comment: I think that I would just add also that John's question touches on an important kind of preconception. And I think that it might be largely based on lack of information. I think that people know more about juvenile salmonid use of eelgrass beds and so there's this perception that they use it preferentially over kelp beds. I think that might be more a product of a lack of looking at kelp beds.

Comment: I would offer that we might also think about nonvegetative areas as well. Maybe what we look at is what Ron hinted at.

Q: Is the continuous eelgrass more valuable than patchy areas?

A: We don't know. That's a very good question. We know edges are more productive, in general, in ecosystems, but if you stand in a meadow at low tide with a foot of water, you can see fish come swim around the edges and come hang around and feed on the edges and crabs will march right in the center of the patch. So there is differential use, but that would be a great study.

Q: How do the kelp beds function? You said that you couldn't really answer that question in the Puget Sound study. What about the Puget Sound study didn't allow you to do that?

A: We didn't look at the invertebrates.

Q: Dr. Norris, I don't think you said what changes had been seen in Port Townsend that may or may not have caused the increase in coverage. Has there been some systematic management effort, or is it just chance?

Norris: The particular area where we estimated basal area coverage has had no significant anthropogenic effects that I am aware of, in terms of dock structures or anything. That's one of the reasons that we chose that particular site. The other example I did mention, though, was the dredging of the eelgrass bed that clearly removed a large amount of eelgrass.

Q: Did you measure factors other than the area of a bed, such as density, length, perhaps?

A: Yes we did. We measured all that stuff. We just presented the density data. As you get deeper, the plants tend to get larger and the density goes down, but there's still 100% cover. So actually cover might be a better thing to look at, rather than density, but we just used the density data here.

Q: Is there a difference in Manchester between the new and the old pier regarding the shading effects given the construction?

A: The new pier didn't show up in my photographs, but the section that crosses the intertidal zone is actually narrower than the old pier was. It's actually a really interesting study because there is a solid part in the middle and then there are just pipes on either side with air between them, and we actually have eelgrass growing underneath that section of the pier. And it's from about minus-one foot below mean low down to about minus-six or seven, and it's slowly filling in those areas underneath the pier. It has been really interesting to see it fill in.

Q: Does the bulk dry density vary between the different laminae? That would effect the accumulation.

A: No, it didn't. And we actually measured the thickness of the laminae. We couldn't measure it well enough, given the data on the x-rays, although there were two or three laminae that were much, much larger – and those actually correspond to seismic events that have happened in the past.

PUGET SOUND RESEARCH '98

SESSION 3A

THE HEALTH OF THE PUGET SOUND AND GEORGIA BASIN ECOSYSTEM

Session Chair:

Scott Redman

Puget Sound Water Quality Action Team

The Health of Puget Sound—An Overview and Implications for Management

Scott Redman
Puget Sound Water Quality Action Team

Introduction

The Puget Sound Ambient Monitoring Program (PSAMP) assesses the health of Puget Sound and its resources through a number of long-term studies. The PSAMP defines five aspects of Puget Sound's health: condition of biological resources; changes in the physical environment; threats from toxic contaminants; threats from pathogens and nutrient contamination; and threats to human health. These monitoring topics were defined by review of a conceptual model of Puget Sound and the human stresses on the Sound and its resources (see Newton et al., 1998b).

This paper briefly presents some recent findings from PSAMP studies and from the work of others. In addition, for each topic, this paper also provides an example of how monitoring data have been, or will be, used to adapt efforts to manage Puget Sound and its resources.

The results presented in this paper are described in more detail in the *1998 Puget Sound Update* (Puget Sound Water Quality Action Team, 1998*)*, a coordinated, comprehensive report from the PSAMP. Presentations at this conference by a number of Puget Sound scientists offer additional details and insights into recent findings about the health of Puget Sound.

Biological Resources

The stocks and populations of many marine organisms in Puget Sound are declining or in poor condition. A 1997 review for the international Puget Sound/Georgia Basin Task Force (see West, 1998) identified 13 species of fish, seabirds, marine mammals and marine invertebrates that are declining in Puget Sound. Among the species of concern are the Olympia oyster, copper rockfish, harbor porpoise, and marbled murrelet.

Several commercially and recreationally important stocks of bottom fish are in poor condition or on the decline (Palsson et al., 1997). Some stocks of other types of fish, notably salmon and herring, are also in poor condition. The proposed listing of Puget Sound chinook and Hood Canal summer run chum as threatened species under the Endangered Species Act underscores the poor condition of fish populations in Puget Sound.

Other findings about the condition of Puget Sound biological resources are less gloomy. The population density of most diving ducks has not declined notably since 1979. Of these marine birds, only scoters and scaup showed declining numbers from 1979 through the mid-1990s (see Nysewander and Evenson, 1998). The acreage and density of kelp along the Strait of Juan de Fuca has remained fairly constant since the late 1980s (see Mumford et al., 1998). Finally, the number of harbor seals living in Puget Sound continues to increase, probably as a result of their protection under the Marine Mammal Protection Act.

Resource managers have used data from the Department of Fish and Wildlife's PSAMP surveys of marine birds to evaluate the threats posed to birds by gillnet fishing. The aerial surveys conducted over the last six years provide useful information on the relative numbers of common murres and rhinoceros auklets that might migrate into locations where gillnets for sockeye could entangle or kill the birds. Resource managers are using these long-term data and additional information from targeted aerial surveys to decide how to regulate the areas and timing of gillnet fishing to minimize entanglement threats to marine birds.

Physical Environment

The development of Puget Sound with buildings, roads, dikes, bulkheads and other structures has changed, and continues to change, Puget Sound's physical environment. One-third of Puget Sound's shoreline has been modified since the time of European settlement (see Berry et al., 1998). These changes can be very disruptive to the ecosystem because of the importance of nearshore areas in supporting sensitive life stages of many marine organisms.

Human activities may also be changing the quality of habitat in Puget Sound's marine waters. Several areas of Puget Sound appear to be susceptible to water quality degradation resulting from excess loadings of nutrients, such as fertilizers and sewage (see Newton et al., 1998a). Environmental managers are concerned that nutrients present at higher than normal levels in these areas could stimulate excess growth of phytoplankton, which could decrease oxygen concentrations in near-bottom waters, and thereby stress bottom-dwelling communities of organisms.

Despite what we seem to know about altered physical environments in Puget Sound, considerable additional information is needed to better inform us about this topic. Management of shoreline development and of nutrient loadings to Puget Sound could be much improved if time series data were better developed and if scientists could describe whether or how much change over time has occurred. Information on rates of change will help resource managers to evaluate whether existing management actions appear to be sufficient.

Toxic Contamination

A number of studies have documented the widespread distribution of toxic contaminants throughout Puget Sound. The results of these studies support previous conclusions that toxic contamination is heaviest and effects are most severe in waters of the Sound's urban areas.

PSAMP studies of the contamination of sediments and fish tissue show that toxics are primarily a concern in urban areas (see, for example, Long and Dzinbal, 1998; O'Neill et al., 1998; West and O'Neill, 1998). Using a broader set of information, the state Department of Ecology has identified 49 contaminated sediment sites (where concentrations exceed regulatory cleanup screening levels) located in urban areas, including Elliott Bay, Commencement Bay, Eagle Harbor on Bainbridge Island, Sinclair and Dyes inlets, Bellingham Bay, Everett Harbor, and Budd Inlet. PSAMP studies show that contamination of fish appears to be closely associated with areas of sediment contamination.

PSAMP data collected from the late 1980s to mid-1990s on contaminants in fish and sediment do not show any trends in concentrations over time. However, concentrations of some toxic contaminants in mussel tissue appear to have declined through the 1980s and early 1990s. For example, PCB concentrations measured in mussel tissue in the 1990s in the Duwamish River and in Elliott Bay are lower than concentrations measured in the 1970s and mid-1980s (Johnson and Davis, 1996). Mussels filter large quantities of water and the observed decrease in concentrations indicates improvement of water quality in Elliott Bay and the Duwamish River.

Information on toxic contamination of fish tissue gathered for PSAMP by the Washington Department of Fish and Wildlife led the state Department of Health and the Bremerton-Kitsap Health district in 1996 to advise people to avoid consuming rockfish from Sinclair Inlet. Data collected by Fish and Wildlife in 1995 showed that fish from Sinclair Inlet accumulated mercury to levels above 1.0 mg/kg. Standards set by the U.S. Food and Drug Administration state that mercury levels above 1.0 mg/kg make fish unsafe for human consumption.

Pathogens and Nutrients

Fecal contamination (an indicator of the potential presence of disease-causing organisms) and

excessive nutrient loadings cause or threaten problems in localized areas around Puget Sound.

Fecal coliform is measured in the marine waters of shellfish growing areas to assure the safety of shellfish harvested for human consumption. The Department of Health has conducted detailed evaluations of conditions at three commercial shellfish growing areas in south Puget Sound from 1991 through 1996 (see Determan, 1998a). Conditions differ in each of these areas, but they may represent patterns that are occurring elsewhere around the Sound:

- In Burley Lagoon, all stations in an area were in compliance with applicable standards and water quality is improving or remaining steady—this may reflect the positive environmental effects of successful local efforts to find and fix pollution problems.
- In Henderson Inlet, current conditions are generally in compliance with applicable standards but concentrations are steadily increasing—this may indicate that population and development pressures could overwhelm existing water quality management efforts and that pollution control efforts should be intensified.
- In Oakland Bay, conditions at some sampling stations are not in compliance with water quality standards though conditions appear to be improving—this may reflect residual problems from localized sources that become apparent after major contaminant sources have been addressed (e.g., the partial renovation of the City of Shelton's sewage system).

Fecal coliform contamination is also measurable in the open marine waters of Puget Sound. Patterns of contamination appear to reflect the input of contamination from freshwater rivers and streams that drain the Puget Sound basin.

Degradation of Puget Sound water quality caused by excess loading of nutrients appears to be limited to semi-enclosed inlets, bays, and passages. The combination of poorly mixed marine waters and excess nutrient contributions from the watershed creates concern primarily in some areas of lower Hood Canal and the bays and inlets of south Puget Sound and the Whidbey basin (see Newton et al., 1998a).

Information on pathogens and nutrients in Puget Sound's waters are used to direct local actions along the shoreline and in watersheds to protect or restore shellfish growing areas and marine water quality. Determan's paper (1998a) in this volume details three examples of the links between water quality monitoring data and watershed management activities related to the protection or restoration of commercial shellfish growing areas.

Human Health

Three types of contamination can threaten human health in Puget Sound: toxic contamination of fish, and fecal (pathogen) and biotoxin contamination of shellfish.

The risks of eating Puget Sound seafood have not been formally evaluated with a risk assessment or health analysis. However, scientists have used the results of a risk assessment of the lower Columbia River to conclude that people consuming English sole from urban areas of Puget Sound or salmon from any Puget Sound location face an increased risk of cancer due to PCB contamination of Puget Sound fishes. The risks to humans from mercury in Puget Sound are not so clear; one of two Columbia River assessment approaches suggests that mercury concentrations observed in Puget Sound rockfish are high enough to cause adverse health effects in fish consumers.

Risks of illness from consumption of Puget Sound shellfish tainted by pathogens and biotoxins are managed by state and local health department programs to evaluate environmental quality at shellfish harvest areas.

Based on relatively high levels of fecal contamination, Washington Department of Health prohibited or restricted harvest of shellfish from many commercial shellfish growing areas in Puget Sound in the late 1980s. More recently, the commercial harvest area subject to downgrades (new

prohibitions or restrictions on harvest) has been nearly balanced by upgrades in classifications for areas where water quality conditions have improved.

Local health districts and the Department of Health also evaluate conditions at recreational shellfish beaches. Evaluated beaches are classified as open or closed to recreational harvest. As of 1996, 52 of 98 Puget Sound beaches that had been evaluated were listed as open to harvest.

To protect shellfish consumers from paralytic shellfish poisoning (PSP), the Department of Health assesses biotoxin concentrations in mussels from a network of sampling locations throughout Puget Sound. As in previous years, high biotoxin concentrations from 1995 through 1997 necessitated temporary shellfish harvest closures for many parts of Puget Sound (see Determan, 1998b). Three sites—two on the Strait of Juan de Fuca and one in Quartermaster Harbor (between Vashon and Maury Islands)—had concentrations of the PSP biotoxin high enough to shut down harvest for more than 100 days through the three year period. Eight more sites had high PSP biotoxin concentrations for at least 30 days during this time. Four of these eight locations are in south Puget Sound where high PSP occurred during an atypical bloom late in the year in 1997.

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Fraser River Action Plan Assessment of Contaminant Effects on Aquatic Ecosystems

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Introduction

The Fraser River Basin is the largest river basin in the province of British Columbia, Canada, draining an area of 234,000 km^2. The basin has significant environmental and commercial value to the province. It supports the largest natural salmon run in the world and the estuary/delta comprises part of the Pacific Flyway for migratory birds. The Fraser River Action Plan (FRAP) is a major ecosystem-wide initiative led by the federal government in Canada to promote the sustainability of the ecological and societal health in the basin. The Plan has several objectives and one was to clean up and prevent pollution in the aquatic ecosystem. A major component of achieving this objective was to assess the current condition of the aquatic ecosystem and its response to contaminants.

Exposure to contaminants has been measured in the basin's aquatic ecosystem through previous studies. For example, elevated levels of dioxins and furans have been measured in sediment and fish in the late 1980s and early 1990s (Mah et al., 1989; Dwernychuk et al., 1991) and elevated levels of chlorophenolics have been recorded for sediment (Swain and Walton 1988) and water (Drinnan et al., 1988; Carey et al., 1988) from sampling conducted in the 1980s.

The FRAP Environmental Quality program utilized four key components of the aquatic ecosystem to track contaminant exposure. The media used were: water, suspended and bed sediment, fish and aquatic-based wildlife. The effects of contaminants and other stressors on the ecosystem were studied in fish, benthic macroinvertebrates and aquatic-based wildlife (birds and mammals). Figure 1 presents the distribution of sampling sites for these media throughout the basin.

For this paper, examples of contaminant results related to suspended sediment, bed sediment and fish tissue from the lower Fraser River and estuary will be presented.

Methods

Sampling of suspended sediment, bed sediment and fish was conducted from 1992 to 1997 at several reaches throughout the basin. Figure 2 presents reaches sampled in the lower Fraser: Agassiz-Lytton reach at the head of the lower Fraser valley, and the North and South arms in the estuary. The Lytton-Quesnel reach (Figure 1) was used as an upstream reference area for comparison to contaminant concentrations measured in the lower Fraser. All media were sampled from the same reaches, where possible.

Suspended sediment was sampled using continuous flow centrifuges; usually one time integrated sample was collected during each sampling campaign per site. Bed sediments were sampled with Ekman grabs from sediment deposition areas in the rivers and four replicate samples were collected per reach. Fish were sampled using beach seines. Fish liver samples consisted of either one or two composite samples per reach; fish muscle samples consisted of five composite samples per reach. Samples were analysed for the following classes of contaminants: dioxins, furans, polychlorinated biphenlys (PCBs), chlorophenolics, polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides, resin and fatty acids, nonylphenolics and trace metals. These were substances that were known or suspected to be associated with known sources in the basin. Details on methods associated with sampling for suspended sediment, bed sediment and fish are presented in Sekela et al. (1995), Brewer et al. (in prep.) and Raymond et al. (in prep.), respectively.

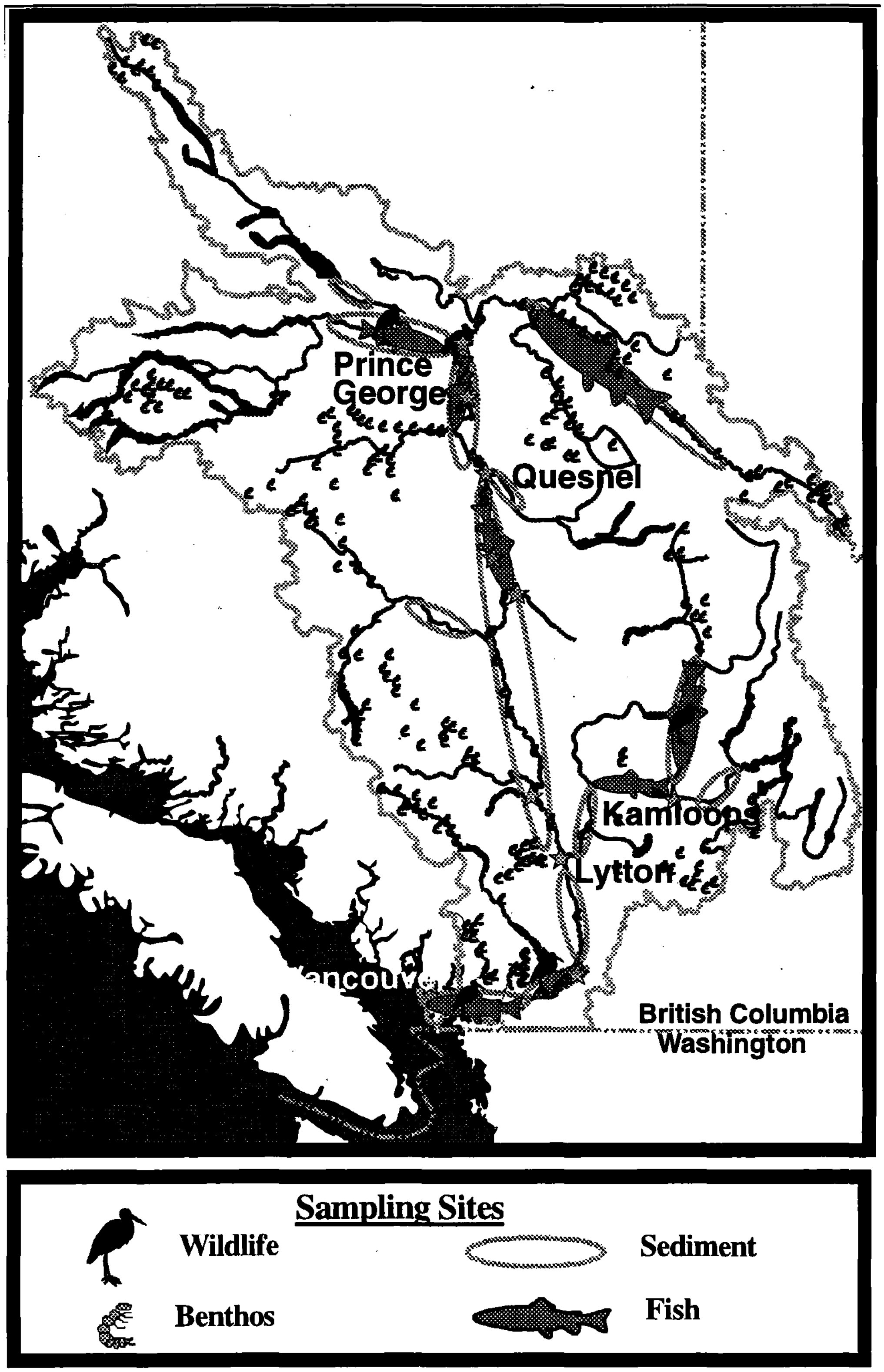

Figure 1. Distribution of sampling sites in the Fraser River Basin.

The Lower Fraser Valley

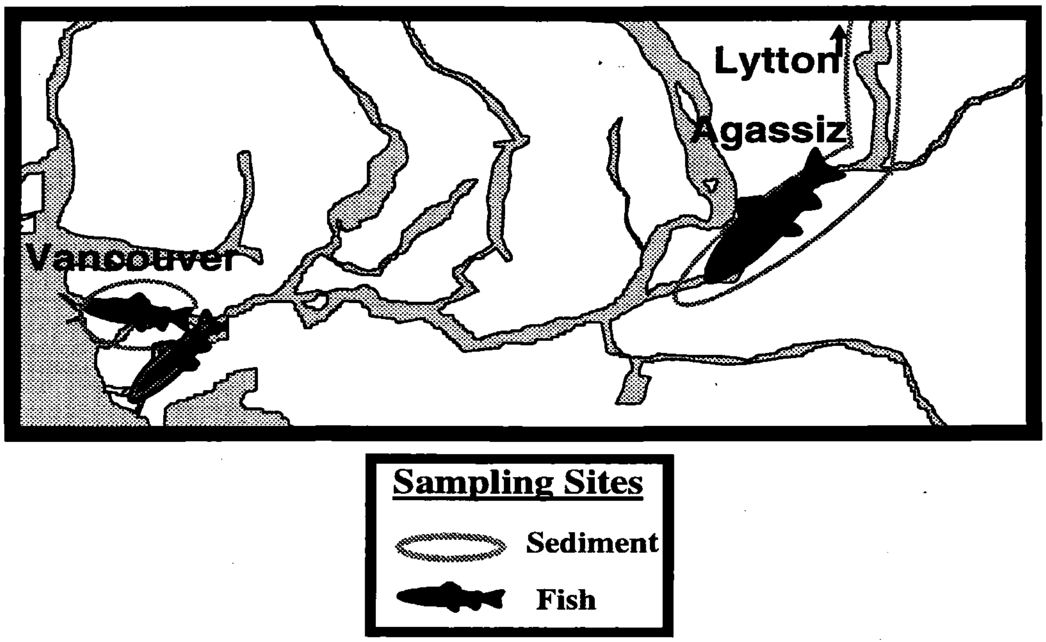

Figure 2. Sampling reaches in the lower Fraser River.

Results and Discussion

The levels of most contaminants in suspended sediment (when expressed as concentration in water), bed sediment and fish tissue from the lower Fraser River were low compared to available Canada Council of Ministers of Environment (CCME) guidelines (CCME, 1994, 1995; CCREM, 1987) and British Columbia Ministry of Environment Lands and Parks (BCMELP) criteria (BCMELP, 1995) for the protection of freshwater life. This is consistent with results found elsewhere in the basin. However, for some classes of contaminants, higher levels were measured in the Fraser estuary than at most most other locations in the basin. In bed and suspended sediment, this was observed for PAHs, dioxins and furans, PCBs, organochlorine pesticides and some metals (arsenic for suspended sediment; arsenic, copper, zinc and lead for bed sediment). Fish tissues had higher levels of organochlorine pesticides and PCBs in the lower Fraser. As well, peamouth chub (*Mylocheilus caurinus*) from the estuary had higher levels of PAHs in liver tissues than fish collected toward the head of the lower Fraser valley. PAHs in fish were analysed only in the lower Fraser.

As an example of the spatial profile of contaminants in the lower Fraser, results on PAHs, dioxins and furans in the three media will be presented here. Detailed results and discussions on all contaminants are presented in Sylvestre et al, (in prep.), Brewer et al. (in prep.) and Raymond et al. (in prep.).

Total parent PAH concentrations in suspended sediment, bed sediment and peamouth chub liver are presented in Figure 3. All three media show the same pattern—higher concentrations in the estuary, with the highest levels measured in the North Arm. Suspended sediment levels for the individual PAH compounds comprising the total parent PAH group, expressed as water concentrations, did not exceed any Canadian water quality guidelines or B.C. water quality criteria for the protection of freshwater life. Bed sediment concentrations exceeded sediment quality guidelines or criteria for the protection of freshwater life for some individual PAH compounds at all sites, the greatest number of exceedences (8) occurred in the North Arm reach.

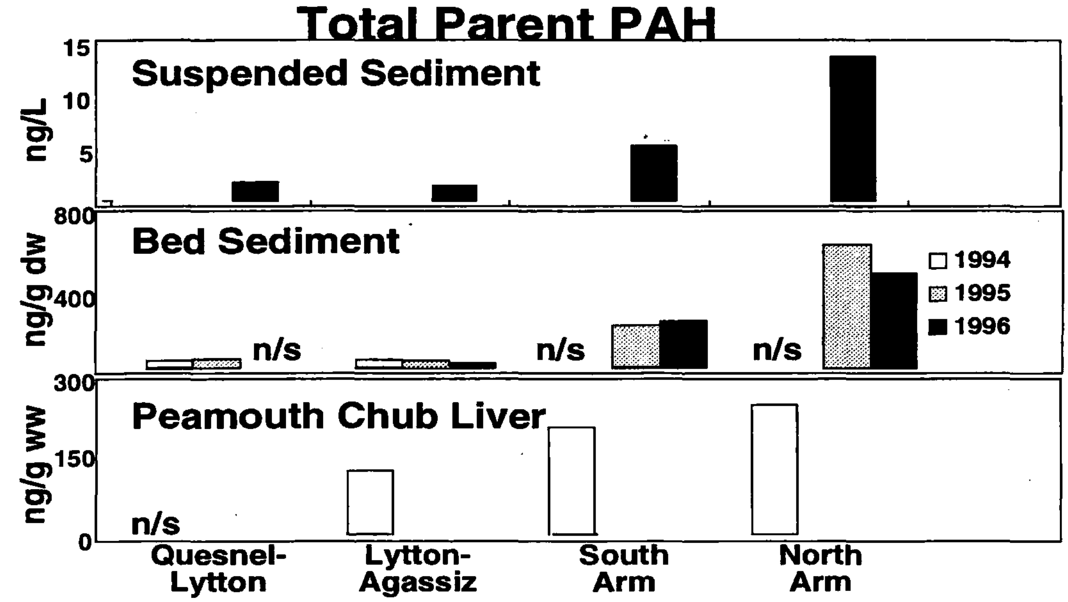

Figure 3. Concentrations of Total Parent PAHs in suspended sediment (expressed as ng/L water), bed sediment and peamouth chub liver from lower Fraser River reaches, and from the upstream Quesnel-Lytton reach. Concentrations in suspended sediment represent a single time integrated sample; concentrations in bed sediment are the mean of four replicates; concentrations of liver represent a single composite value or the mean of two composites. n/s denotes not sampled.

Higher concentrations in the North Arm are likely due to the diminished ability for dilution of inputs by the river, as the North Arm carries about 12% of the river flow at the division of the main stem of the river to North and South Arms (FREMP, 1996). Other factors contributing to the higher PAH levels in the North Arm are likely the presence of combined sewer inputs, as well as a greater number of stormwater discharges, relative to the South Arm (FREMP, 1996). The North Arm is surrounded by dense urban development. Known sources of PAHs include many related to urban activities, such as urban runoff (Boom and Marselek, 1988), combustion of organic material, industrial combustion, wood burning and automobile exhaust (Water Quality Branch, 1993).

Dioxin and furan exposure in suspended and bed sediment shows the same spatial pattern as PAHs—highest concentrations in the North Arm (Figure 4). The concentration in suspended sediment (expressed as pg/L water) approaches the CCME interim water quality guideline for the protection of freshwater life (CCME ,1995). All the bed sediment levels in the lower Fraser River exceed the CCME interim sediment quality guideline. Several other sites elsewhere in the basin also exceeded this interim guideline. Brewer et al . (in prep.) suggest that the dominance of octachlorodibenzoparadioxin (OCDD) in the congener profile for both bed and suspended sediment in the lower Fraser River indicate that combustion sources (Czuczwa and Hites, 1986) are significant contributors of these contaminants in the estuary. The North Arm congener signal (combination of hepta- and octa-dioxins and furans) is also consistent with a pentachlorophenal source (Czuczwa and Hites, 1986), possibly a remnant of past pentachlorophenal usage at lumber mills in the North Arm (Brewer et al., in prep.).

Dioxin and furan concentrations in peamouth chub muscle show low levels and a similar pattern to the sediment data. The levels are well below the CCME interim wildlife dietary guideline (CCME, 1995). The major contributor to the toxic equivalent unit is the 2,3,7,8-tetrachlorodibenzofuran congener (Raymond et al., in prep). This suggests remnants of past contamination and possibly low level current contamination from upstream pulp mills (Amendola,1987). In 1991 basin pulp mills were required to change their bleaching process by substituting chlorine dioxide for elemental chlorine to reduce the discharge of dioxins and furans to the environment.

Dioxin and furan concentrations show decreases when compared to pre-1991 data. Large decreases are seen in bed sediment levels in the upstream Lytton to Quesnel reach, where concentrations were up to about 42 pg/g Toxic Equivalent Unit (TEQ) in 1988 (Mah et al., 1989). Levels at that reach were at 0.05 pg/g TEQ in the current study. Bed sediment concentrations in the estuary are similar to those measured prior to 1991 (Brewer et al., in prep.). Pre-1991 concentrations in peamouth chub muscle were measured at 15 pg/g TEQ in the upstream reach in 1988 (Mah et al., 1989). In the estuary, concentrations were about 2 pg/g TEQ in peamouth chub collected in 1989 (Tuominen and Sekela, 1992). Concentrations today are less than 0.14 pg/g TEQ, more than an order of magnitude lower than pre-1991 levels.

Decreases in other contaminants, such as PCBs, pentachlorophenol, organochlorine pesticides and lead, relative to pre-1991 levels were also found in the lower Fraser (Brewer et al., in prep; Raymond et al., in prep.; FREMP, 1996). These decreases are due to the introduction of regulations to control their use or discharge to the environment.

The increase in concentration of contaminants in the estuary, relative to other basin areas, is attributed to human activities in the surrounding urban landscape. This effect was more pronounced in a FRAP study conducted in an urban tributary of the estuary. Because of less dilution potential in the tributary, even higher concentrations of the same contaminant classes (e.g., PAHs, dioxins and furans)

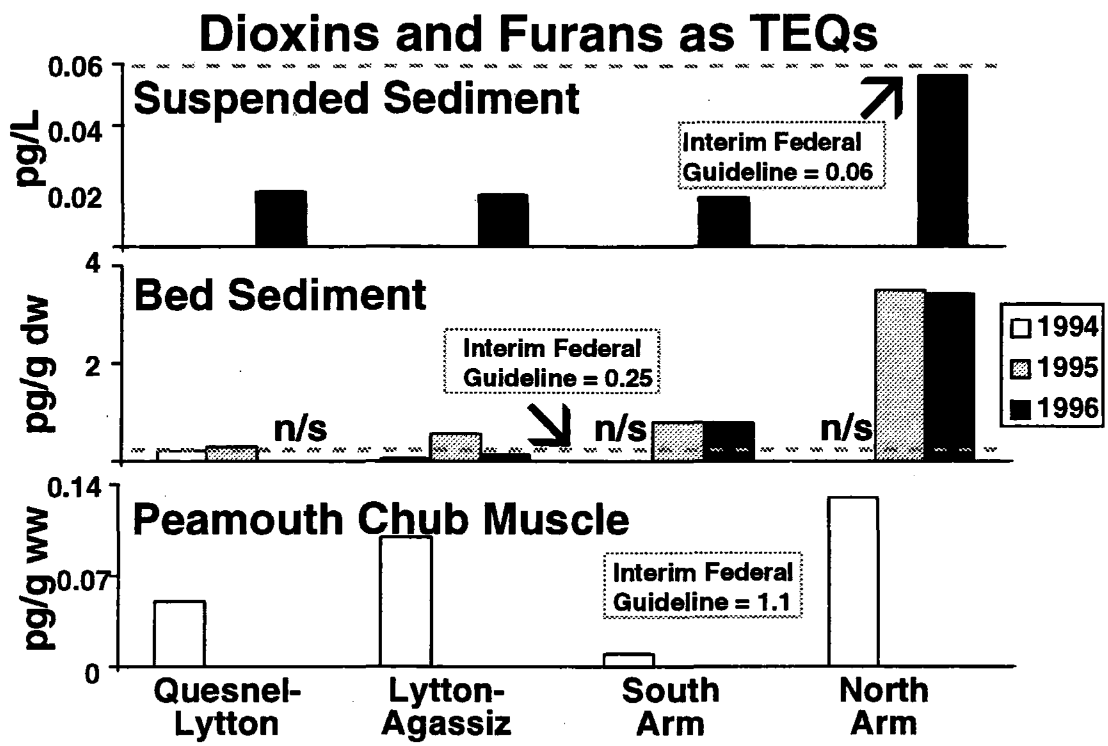

Figure 4. Concentrations of dioxins and furans, as 2,3,7,8-tetrachlorodibenzo-para-dioxin Toxicity Equivalent Units, in suspended sediment, bed sediment and peamouth chub muscle tissue from lower Fraser River reaches, and from the upstream Quesnel-Lytton reach. Concentrations in suspended sediment are expressed as pg/L water and represent a single time integrated sample; concentrations in bed sediment are the mean of four replicates; concentrations in muscle are the mean of five composite samples. n/s denotes not sampled.

were measured in the tributary's aquatic ecosystem than in the Fraser River (Sekela et al., in prep.).

Conclusions

1. Most contaminants in suspended sediment (expressed as concentration in water), bed sediment and fish tissue from the lower Fraser River were measured at low levels compared to Canadian federal guidelines and provincial criteria for the protection of freshwater life. This was consistent to results found elsewhere in the basin. Exceptions included PAHs in bed sediment from the estuary and dioxins and furans in bed and suspended sediment from the estuary.
2. Concentrations of some contaminants, such as pentachlorophenol, lead, PCBs, dioxins, furans and organochlorine pesticides have decreased since pre-1991.
3. Signs of urban activity in the estuary are evident in elevated levels of some contaminants, such as PAHs dioxins, and furans, particularly in the suspended and bed sediment, compared to upstream levels.
4. With the projected growth in population in the lower Fraser River (by about 50% in the next 20 years [GVRD, 1997]), stress on the aquatic ecosystem of the estuary from contaminants, such as PAHs, is likely to grow.

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Puget Sound's Maritime Industries—The Health of Puget Sound: An Alternative View

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Washington Sea Grant Program

Introduction

Most of the presentations you will have heard at this conference will have dealt with the physical health of Puget Sound: water quality, habitat integrity, aquatic species diversity and abundance, and so forth. In this paper I address another dimension of Puget Sound's health: The capacity of its shorelines to sustain the cultural, social and economic well being of the region's peoples.

The cultural/historical health of the shorelines can, in part, be sustained by celebrating the Sound's historic role in shaping cultures and history, restoring and preserving historic shoreline structures, and protecting and interpreting culturally important sites. We can ensure that historically significant buildings and sites of important events are not lost through neglect; and we can mark and interpret them through exhibits and interpretive programs. In this fashion we can celebrate the many ways the Sound has shaped us and those who were here before us.

The social health of this maritime region is enhanced by protecting and enhancing public access to and from the Sound, maintaining per capita share of shoreline parks and open space, and enabling safe and diverse recreational uses of the water surface and water column. As our region's population grows we can expand the opportunities for the public to reach the Sound and to recreate beside, in, and on the water; and to do this in ways that allow diverse uses and users to enjoy the experience safely.

Sustaining the health of our maritime economy is achieved by giving priority to water-dependent industry in shoreline siting decisions, reserving sites for deep draft vessels, ensuring compatible upland uses, and maintaining adequate landside transportation infrastructure.

Our limited shores provide the only sites where certain industries can manufacture the products we need and provide the services we demand, and where ports can move the goods we consume. We need to give these uses priority over those that can prosper across the street from the water's edge, or on sites far inland. We also need to avoid unwittingly creating conflicts by permitting inappropriate upland uses to interfere with the functioning of those uses that depend on a shoreline location. The federal Coastal Zone Management Act and the state's Shoreline Management Act (SMA) both embrace these fundamental coastal planning principles (Wagner, 1985). The research project reported in this paper addressed this last dimension of an alternative "Health of the Sound" viewpoint.

Objectives

Research Questions

In a Sea Grant-supported project that began in 1983 and was updated in 1995–96, we asked four questions concerning the sustainable economic health of the Sound:

- What kinds of commercial/industrial establishments occupy shoreline parcels?
- Which industries are water-dependent?
- How has the mix of shoreline industries changed over time?
- Has shoreline management been effective in protecting water-dependent (W-D) industries?

Answers to the first two questions have been published elsewhere (Goodwin, 1987).

The industry inventory of Puget Sound's urban harbors was updated in 1995–6 to include 1992 data, and the region-wide changes occurring over the 1962–92 period were reported in a paper presented last year (Goodwin, 1997). Answering the final question involves analyses of both shoreline industry data and case studies of shoreline management decisions.

The loss of W-D firms from the shorelines of Puget Sound can be caused by many factors:

- business failures due to competition from domestic or foreign firms in the same industry
- retirement of principals
- displacement by non-W-D businesses competing for the same site

Shoreline management, through control of land and water uses and development regulations, can only address the last of these—displacement. Consequently, it is important to examine case examples of shoreline management decisions to understand the role it has played. The real story concerning displacement is found in the details of such individual cases, not in the gross numbers of businesses moving from (or within) the shorelines of Puget Sound.

While this is not, strictly, a land use study, nor an economic analysis in the sense of measuring changes in dollar output or jobs, it *does* reveal the consequences of land use decisions through an examination of the changing industrial structure of our urban shorelines.

Methods

A comprehensive study of Puget Sound's urban harbors was conducted during 1983 and 1984. Harbor-by-harbor inventories of commercial and industrial establishments occupying waterfront parcels were created for the years 1962, 1972, and 1982. These intervals were chosen to coincide with Bureau of Census' economic reports and to reveal changes during the decades before and after passage of Washington's Shoreline Management Act in 1971.

Washington State's Department of Revenue (DOR) provided the researchers with a tape containing records of all firms located in urban coastal zip code areas around Puget Sound in 1982. Firms paying either Business and Occupation (B & O) tax or state sales tax appeared in this file. An attempt was made to partition the records into shoreline and upland addresses; but a high proportion of firms reported either from post office boxes, or from corporate headquarters located outside the shoreline.

The researchers turned to city directories, where available, to construct inventories of shoreline businesses for the years 1962, 1972, and 1982. For each firm extant in 1982, an attempt was then made to match it with DOR records (available only in electronic form from 1975 onwards). Site visits were made to verify the location of shoreline addresses: i.e., those with direct access to water. Unmatched firms were assigned SIC numbers from their description in directories, or from direct contacts with firms' officials. Sparse descriptions of firms listed in city directories for earlier years, but no longer extant, provided little guidance for assigning SIC numbers. These firms were classified with the code 9999.

While the larger waterfront cities on Puget Sound have city directories dating back to years prior to 1962, smaller communities often are covered only for recent years, or not at all. Combining information gleaned from DOR files with site visits generated 1982 inventories for harbors without contemporaneous city directories, but reconstructing inventories for early decades proved unfeasible.

The meaning of "shoreline establishments" was difficult to ascertain where a firm was located on port lands adjacent to waterways. Even where the establishment was located at some distance from the water's edge, access to water over common roads, docks, or ramps was usually available. For this reason, all firms on port lands contiguous to waterways were defined as shoreline establishments.

Establishments utilizing submerged lands, but having no proprietary interest in contiguous waterfront land parcels were excluded; aquaculture tracts and log-booming sites frequently fell into this category. Also excluded from the inventory were fishing boats because, even though many of these vessels

are considered corporations, they are not permanent uses subject to shoreline land use regulation. However, the firms or port authorities leasing the docks and marinas where these vessels are moored are included.

Further ambiguities arose where streets had been renamed, or where new shoreline landfills had occurred during the two decades under study. Some addresses changed from shoreline to upland as a consequence and were deleted from the inventory in subsequent years.

In 1996, the investigators purchased a proprietary database of firms located in coastal ZIP Code areas in 1992. Many of the same data issues arising in earlier decades resurfaced—i.e., firms listed only at their headquarters offices, or reporting P.O. boxes rather than addresses. Site visits were made to supplement and verify questionable data. Complicating the assignment of firms' SIC codes were the revisions to the SIC Manual in 1972 and 1987, which, in some cases significantly affected the level of aggregation of industries.

The degree to which an industry is *concentrated* on shoreline sites is a measure of its water-dependency. For example, marine cargo terminals are to be found only at the shoreline; restaurants, on the other hand, are virtually ubiquitous. In between those extremes, some seafood processing plants are found at both shoreline and inland sites and thus exhibit a less-than-absolute coastal dependency. Technological change, particularly in transport systems, has weakened some industries' coastal dependency. Fish, once delivered fresh to a dockside cannery from a fishing boat, now may move by common carrier in refrigerated containers, or as frozen product to an inland processing plant. Similar shifts in water-dependency are to be expected in segments of the forest products industry, petroleum products wholesale and distribution centers, and in sand and gravel and batch concrete firms. Using "Location Quotients"—a simple geographic measure of regional industrial concentration—industries showing a significant degree of concentration in the shoreline were identified (Goodwin, 1987).

Industries appearing in Seattle's urban shorelines were partitioned into three groups. Water-dependent and water-related industries serving primarily recreational markets (marinas, boatyards, boat dealers, yacht clubs, etc.), and those serving commercial/industrial customers (marine transportation, marine cargo handling, fish-processing, etc.), were defined as "recreational water-dependent" and "industrial water dependent," respectively. All remaining industries were considered non-water-dependent.

Results

Puget Sound's Harbors 1962–92

Figure 1 shows the number of establishments (individual firms at particular locations) on waterfront parcels in selected Puget Sound harbors for which data were available for each decade since 1962 (Bellingham, Bremerton, Everett, Olympia, Port Angeles, Seattle, and Tacoma).

It is easy to see where the growth has occurred: retail trade, finance, insurance, and real estate (F.I.R.E) firms, and services—industries that comprise the tertiary sector of the economy—have all grown strongly in the last 30 years. But the number of businesses engaged in construction, manufacturing, transportation and wholesale trade—the secondary sector of the economy—has been relatively stable.

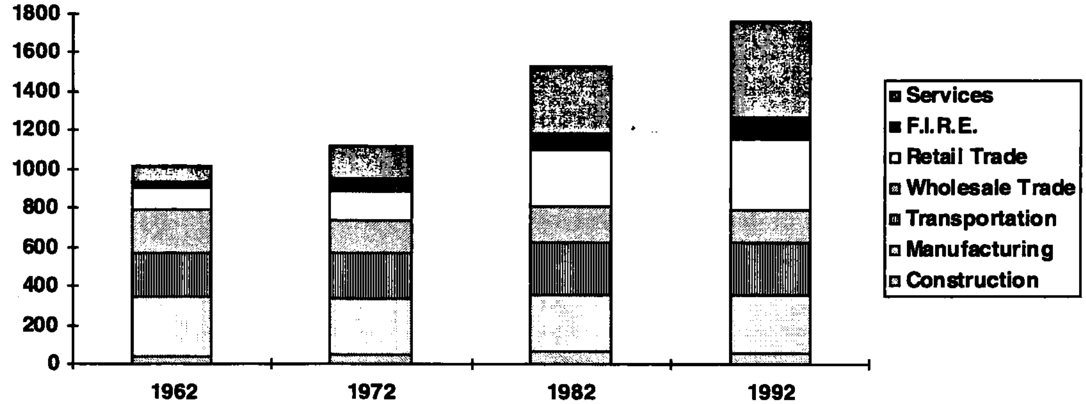

Figure 1. Puget Sound harbors: number of shoreline establishment by industrial sector, 1962–92.

But this is not the whole story, by any means. Puget Sound's harbors have grown (or shrunk) differentially, and much variation is revealed at the individual harbor level. Examining Seattle's shorelines in 1992, the year for which we have the latest data, there are dramatic differences in the mix of industries occupying shoreline parcels among the city's three main commercial/industrial harbor reaches. Figure 2 displays the percentage distributions of firms in industrial sectors in each reach over the four decadal time points.

On the Duwamish Waterways, firms engaged in manufacturing, transportation, and wholesale trade dominate the shoreline. Retail trade, finance, insurance and real estate, and services play a minor role. But on the Lake Union/Lake Washington Ship Canal shorelines, the situation is reversed. The tertiary sector is dominant: services, retail trade, and finance/insurance/real estate account for almost 70% of firms. Harborfront has the highest concentration of retail activities among the three harbor areas, but still retains a significant regional marine transportation role, primarily passenger ferries.

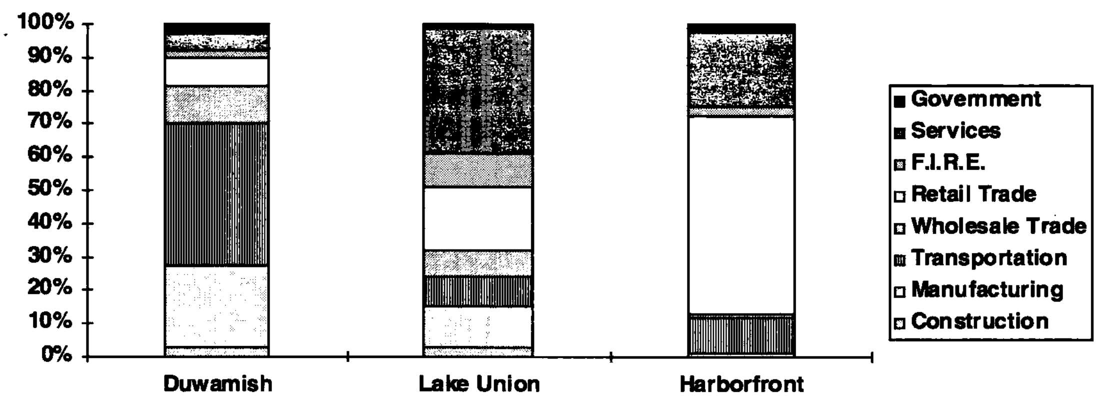

Figure 2. Seattle harbors: percentage of shoreline establishments by industrial sector, 1962–92.

Harborfront

Anyone old enough to remember the Seattle World's Fair will also recall a very different Harborfront from the one we see today. Already abandoned by steamship lines, the downtown piers and transit sheds in 1962 still served the wholesale trade, especially in fish, paper, and cans. But, as Figure 3 shows, wholesale trade has given way to retailers and tourist services. Harborfront has been revitalized; many of the historic pier sheds have been adapted for retail and "water enjoyment" uses—aquariums,

museums, restaurants—while their perimeters still serve marine transportation and moorage needs, and permit public access to the water's edge.

When we break out firms by the kind of dependence they have on a waterfront location (Figure 4), we see that non-water-dependent establishments (e.g., office, retail, restaurant) have more than doubled. In contrast, water-dependent (and water-related) firms of an industrial nature (marine transportation, marine cargo handling, fish-processing, etc.) have diminished by 75%. Recreational water-dependent enterprises have played only a minor role until recently. (The new Bell Harbor short-stay marina and related businesses built since 1992 are not captured in these data).

Over the same 30 years, the Duwamish (including Harbor Island) has retained its gritty industrial character (see Figure 5). Its marine transportation terminals have grown in importance. Shore-based manufacturing—including cement, steel and non-ferrous metals, lumber, seafood, and shipbuilding, and much of the region's heavy marine construction industry—is based here.

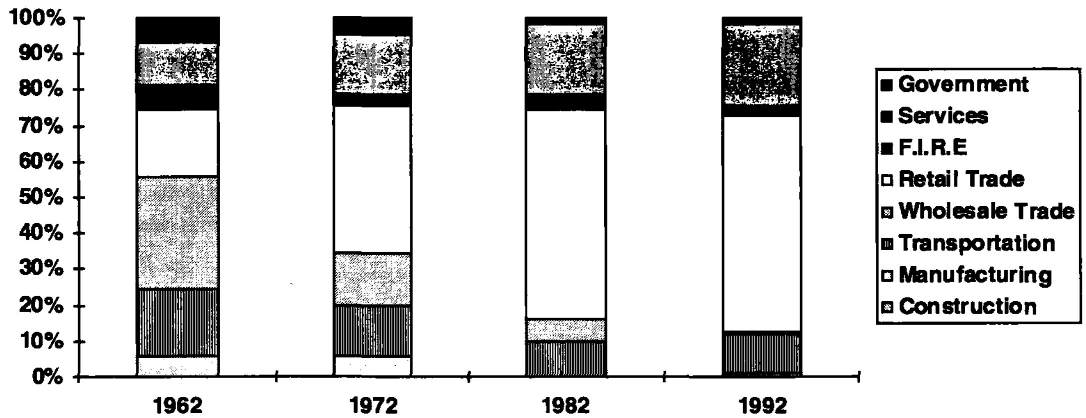

Figure 3. Seattle's Harborfront: percentage of shoreline establishments by industrial sector, 1962–92.

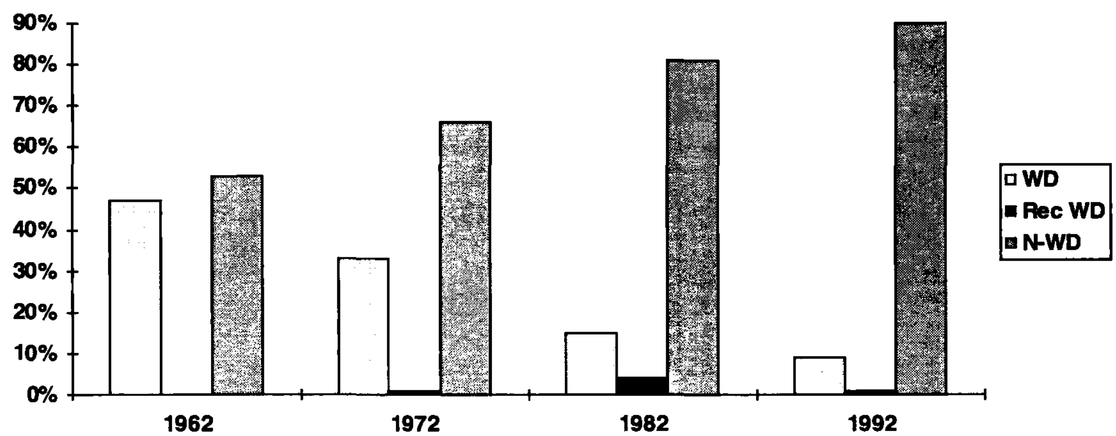

Figure 4. Seattle's Harborfront: percentage of shoreline establishments by type of water-dependency, 1962–92.

Industrial water-dependent industry has maintained a clear majority of businesses over the three decades. Non-water-dependent businesses have undergone a decline, while purely recreation-oriented non-water-dependent firms have scarcely made an inroad into this industrial waterfront territory. Figure 6 shows this relative stability.

Lake Union is intensely developed and supports multiple uses, including restaurants, fishing-support industries, marinas and boatyards, yacht brokerages and the region's busiest air harbor. The lake is surrounded by intensively developed uplands in residential and commercial uses.

Figure 7 shows that changes in the secondary sector along the lake and Ship Canal's shores were undramatic, but persistent: manufacturing, transportation, and wholesale trade's share has declined. The tertiary sector, led by services and retail trade, surged ahead. Over-building of offices prior to passage of the SMA resulted in vacancies that filled over the following decade. Adaptive reuse of warehouses and other industrial structures for office use has also occurred, and new mixed use developments that provide public access and transient moorage have been developed at the south end of the lake.

Water-dependent uses—both industrial and recreational—have grown in number, and the latter have almost pulled ahead (Figure 8). Non-water-dependent uses, once representing a minority of businesses on the lake, now outnumber water-dependent uses as office space built prior to shoreline management has been leased up.

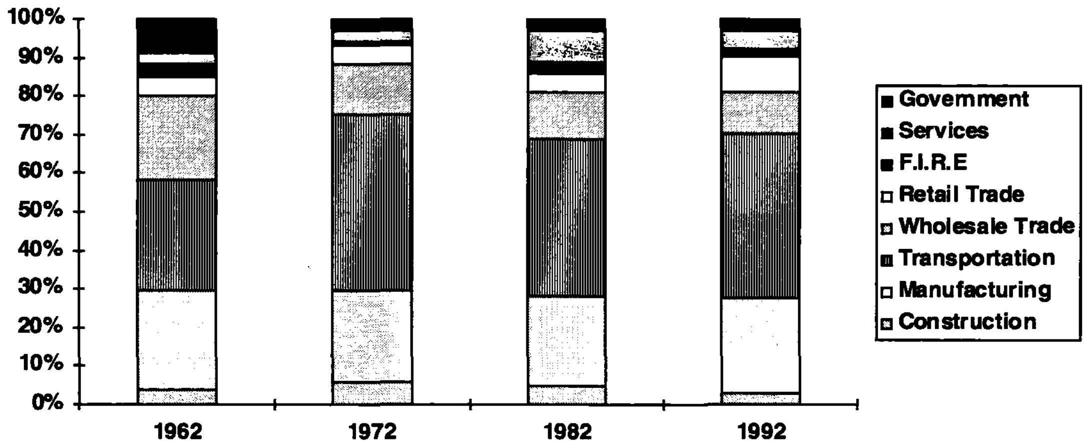

Figure 5. Seattle's Duwamish waterways: percentage of shoreline establishments by industrial sector, 1962–92.

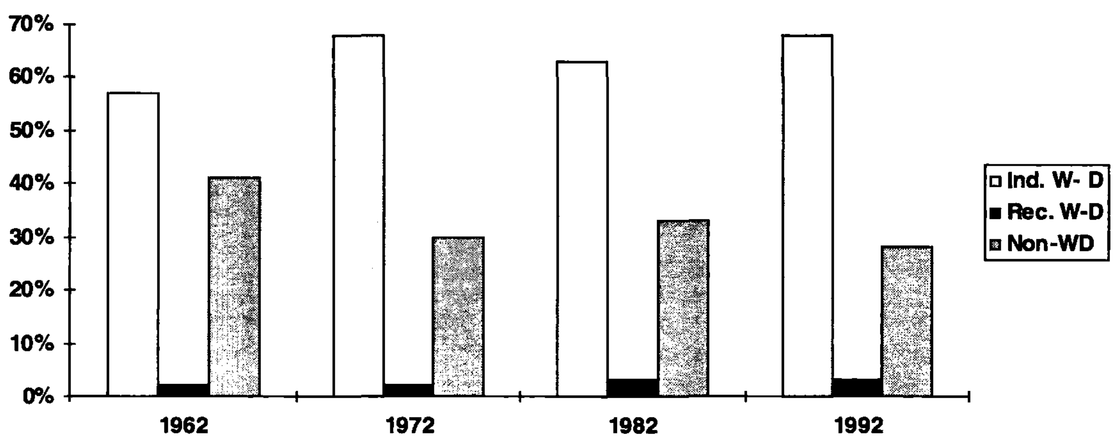

Figure 6. Seattle's Duwamish waterways: percentage of shoreline establishments by type of water-dependency, 1962-92.

Conclusions

Has shoreline management been effective in giving priority to water-dependent uses? Let's now return to the final research question we asked: How effective has shoreline management been in protecting and enhancing W-D businesses in the shorelines? The evidence is mixed.

Evidence for:

On the one hand we see that the industrial integrity of the Duwamish seems intact, and that W-D uses have grown, not diminished along the Lake Union/Ship Canal shorelines.

Evidence against:

On the other hand, we see a continued increase in the number of non-W-D uses on Lake Union, and dramatically increasing retail activity on Harborfront. But indications of success are found in the details. No new principal-use office buildings have been permitted on Lake Union, and W-D uses, where permitted, have been required to provide generous amounts of public access and other amenities (City of Seattle, 1987).

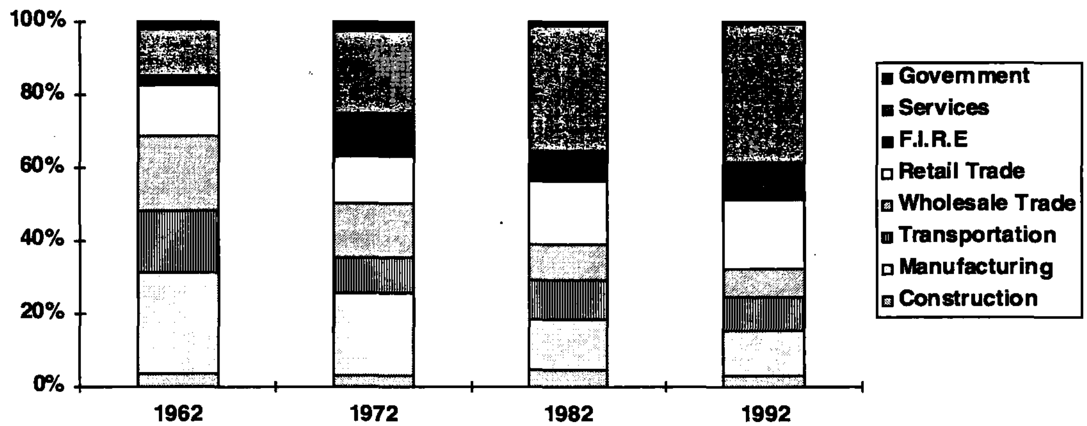

Figure 7. Seattle's Lake Union/Ship Canal: percentage of shoreline establishments by industrial sector, 1962–92.

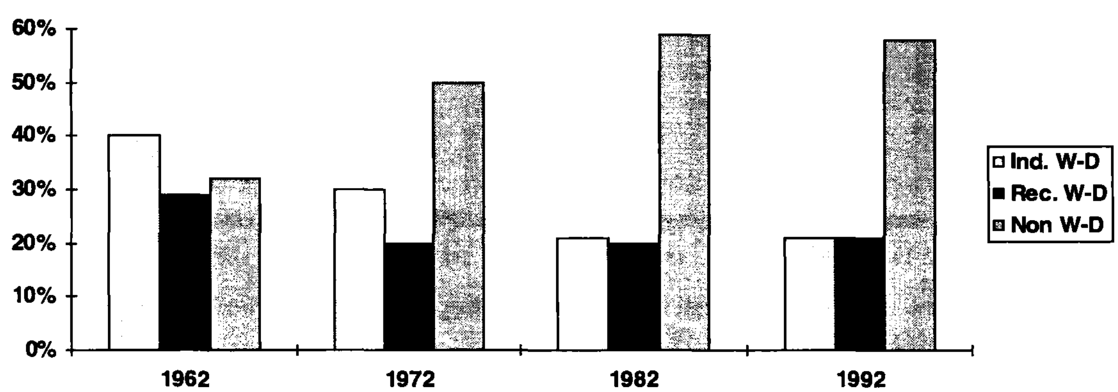

Figure 8. Seattle's Lake Union/Ship Canal waterways: percentage of shoreline establishments by type of water-dependency, 1962–92.

Along Harborfront, owners of historic pier sheds are permitted to incorporate retail shops and restaurants in redeveloped piers, but must improve and maintain the pier aprons for public access and vessel moorage. Consequently, Harborfront's redeveloped piers support marine activities such as moorage for tour boats and large fishing vessels.

A number of sites on Lake Union and the Ship Canal have been designated for water-dependent maritime and industrial uses, such as cargo handling, fishing vessel moorage, shipyards, and water-related manufacturing. In one case, a developer had sought City Council approval for a variance to permit a mixed-use, non-water-dependent development on a site designated "Urban Industrial." The council held firm, however, and their decision was vindicated when the former water-related industrial site (Champion Plywood) was redeveloped by an intracoastal marine transportation company servicing the Alaska trade, a water-dependent industrial use. Other small marine firms co-located on this site.

Implications

Returning to my original precepts, it is clear that maintaining a healthy Puget Sound involves at least three considerations beyond the biological and physical health of the waters and beds of the Sound. Conserving our cultural and historic marine heritage, enhancing public access to the water and giving priority to water-dependent industry are some of the other ways we sustain a healthy Sound.

But not all of these goals can necessarily be achieved at the same time on the same site: public access and marine industry are often in conflict, and historic restoration and conservation may be economically unfeasible without rental income from non-water-dependent tenants. Priorities have been established among these goals for each of Seattle's three principal harbor reaches, and are backed by state law and local ordinances. They were informed by thorough analyses of the physical and economic characteristics of the shorelines, and the likely trends in shoreline use (City of Seattle, 1983).

At time of writing, the Port of Seattle is contemplating undertaking another comprehensive assessment of the demand for and supply of shoreline land for industrial maritime use. It is this author's hope that the shoreline land use trends reported in this paper, together with prior City of Seattle studies, will help inform their assessment and guide the Port Commission in making prudent and strategic land allocation commitments. The stock of shorelands suitable for marine industrial use is limited. Thoughtful conservation and reuse of urban industrial shorelands we now have will help avoid contentious siting decisions in the future and prevent industrial encroachment on rural shorelines.

Acknowledgments

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The Health of Puget Sound—Measures of Puget Sound's Environmental and Natural Resource Health

Kevin Anderson
Puget Sound Water Quality Action Team

Introduction

In 1996, the Washington Legislature directed the Puget Sound Water Quality Action Team to develop and track measures of the health of Puget Sound's water quality and natural resources. This report outlines the method used by the Action Team to develop them. It also summarizes the Sound-wide status and trends of each. Performance measures will be used to assess how well the Puget Sound Water Quality Management Plan protects and restores the biological health and diversity of Puget Sound. Future activities will focus on using these measures to build constituencies, educate citizens about Puget Sound's environment and to set resource management program priorities.

Legislative Mandate and Guidance

The Puget Sound Water Quality Protection Act of 1996 directed the Puget Sound Water Quality Action Team to develop performance measures. The governor and the legislature will use these measures to assess the effectiveness of the Puget Sound Plan.

> In consultation with state agencies, local and tribal governments, and other public and private interests, the action team shall develop and track quantifiable performance measures that can be used by the governor and the legislature to assess the effectiveness over time of programs and actions initiated under the plan to improve and protect Puget Sound water quality and biological resources. The performance measures shall be developed by June 30, 1997. The performance measures shall include, but not be limited to a methodology to track the progress of: Fish and wildlife habitat; sites with sediment contamination; wetlands; shellfish beds; and other key measures of Puget Sound health. State agencies shall assist the action team in the development and tracking of these performance measures. The performance measures may be limited to a selected geographic area. (RCW 90.71.060)

The Puget Sound Action Team will use these measures to help set water quality and resource protection priorities in developing the state's biennial Puget Sound work plan and budget. Performance measures will be used to inform the general public and policy makers about the health of the Sound. Future work may focus using measures to inform the development of watershed assessments and plans.

Objectives

To meet the requirements of the Act, the Puget Sound Water Quality Action Team chair outlined the following broad objectives for developing Puget Sound health measures:

- Use an advisory group to develop and recommend measures.
- Characterize environmental results of programs, rather than program activities.
- Keep the list of performance measures short.
- Develop measures from data that agencies already have or plan to obtain and rely on those agencies for data analysis.
- Identify performance measures for which data is not currently available.
- Select measures to serve a variety of audiences, including the governor and legislature.

Methods and General Design Considerations

For the purposes of this project, the Action Team used the following "performance measures" terminology. Performance measures are a thumbnail status report on the health of the environment or natural resources and provide an early warning of problems.' These measures do not explain the causes of problems. They may be reported in terms of reference points, such as benchmarks or goals, or as positive or negative trends.

The Action Team convened an advisory group composed of tribal, state and local governments, and business and environmental interests to recommend performance measures, data collection strategies and to identify gaps in both. The group met several times.

The advisory group identified a set of real-world, frequently asked questions relevant to Puget Sound's environmental health. Performance measures were identified around these questions. They are designed to resonate with the general public. The real-world questions addressed the following environmental and resource management topics: aquatic habitat, fish and wildlife populations and habitat, exotic species, toxic discharges, oil spills, wetlands, shellfish and contaminated sediment sites. These topics are identified in the:

- Puget Sound Water Quality Protection Act (RCW 90.71.060);
- Puget Sound Water Quality Management Plan; and
- Marine Science Panel's Shared Marine Waters of British Columbia and Washington.

To ensure coordination with other projects, the Action Team support staff and the advisory group reviewed ongoing environmental indicator projects and potential measures related to each environmental and resource management topic. These projects included the Puget Sound Ambient Monitoring Program, the U.S. Environmental Protection Agency, Washington State Department of Ecology, British Columbia's Ministry of Environment, Lands and Parks and other projects. All potential measures, from these projects and from others identified by the group, were ranked using the following broad criteria:

- Value to the public;
- Relevance to Puget Sound environmental management;
- Technical merit; and
- Practicality.

Top ranked measures were tested by small groups of interagency specialists. The tests showed the relationship between the health of the environment and program actions for each topic area; assessed data availability and refined selected performance measures.

Recommended Performance Measures

The Puget Sound Water Quality Action Team adopted the recommended performance measures listed in Table 1.

Results

The Action Team prepared a Sound-wide status and trend analysis of each Puget Sound health measure. A synopsis of these trends is included in Table 2: Puget Sound Environmental Trends. Table 3: Data Sources summarizes data sources used to populate each measure. Data from various sources were used in this analysis. Some measures have insufficient data to show trends over time. These are listed as "baseline" measures and provide a reference against which future changes can be assessed.

To the extent possible, each measure will be reported on both a Sound-wide and watershed level. Performance measures will also be reviewed annually and, when appropriate, updated and reported in a variety of formats.

Table 1. Puget Sound performance measures

Question	Performance Measure
1) Are fish and wildlife populations increasing or decreasing?	• Status of key species: scoter, herring, wild salmon and harbor seals.
2) Is the area of contaminated sediments increasing or decreasing?	• Area of Puget Sound sediments known to be contaminated. • Area of Puget Sound sediments restored.
3) Are toxins in the marine environment increasing or decreasing?	• Metals and organic contaminants in mussels and English sole.
4) Are safe shellfish harvest areas increasing or decreasing?	• Change in acreage of classified shellfish growing areas based on sanitary conditions
5) Is water quality for recreation improving or declining?	• Levels of fecal coliform bacteria at selected nearshore and river sites.
6) Are the size and frequency of oil spills increasing or decreasing?	• Frequency and volume of oil spills from vessels and shore-based facilities.
7) Is functional fish and wildlife habitat increasing or decreasing?	• Area of habitat inaccessible to salmon because of human-made barriers. • Additional fish and wildlife habitat measures will be identified.
8) Are functional wetlands increasing or decreasing?	• Wetland measures will be identified. There is currently inadequate information to support Sound-wide reporting on wetlands measures.

Next Steps

The following are the next steps related to the Puget Sound performance measures project.

1) Fresh and Marine Water Wetlands and Fish and Wildlife Habitat Measures: The Action Team recognized that there was not enough information to support Sound-wide reporting on wetlands and habitat measures. They directed staff to investigate and recommend measures and data collection strategies for determining long-term trends in the quality and quantity of fresh and marine water wetlands and habitat.

Table 4 was developed with help from an interagency work group. These measures and potential data sources were presented to the Puget Sound Water Quality Action Team in February 1998. The Action Team directed staff to use these recommendations as the basis for developing measures and data collection strategies that are coordinated with ongoing salmon protection and restoration efforts.

2) Improve Coordination and Cooperation: Many government agencies and private groups are working on similar projects at different scales and within different time frames. Some of these projects have developed and use measures for water quality and biological resources in the Puget Sound basin. While some projects share common goals, there are numerous approaches to collecting and using measures.

The Action Team plans a one-day workshop to provide opportunities for government and private practitioners to network and cooperate on development and use of performance measures. The workshop will explore collaboration opportunities and discuss the uses of measures in management and for public education and involvement.

3) Publish and Update Performance Measures: The Action Team is in the process of publishing a report on the status and trends of each performance measure. The report will be written for public consumption. In addition, each performance measure will be reviewed annually. Updated status or trends information will be made available through supplemental publications or through the Action Team's newsletter and web page.

Table 2. Puget Sound environmental trends.

Performance Measure	Increasing	Declining	No change	Baseline	Significance
Are fish and wildlife populations increasing or decreasing?					
Pacific herring stocks				X	Of 18 stocks, 1 is critical, 3 are depressed.
Pacific herring populations		X			Steady declines since 1975, significant declines in 1996-'97.
Salmon and steelhead stocks				X	27% of the Sound's 209 stocks are critical or depressed.
Scoter populations		X			50% decline in population since 1979.
Harbor seal populations	X				6% annual increase in populations since 1975.
Are functional wetlands increasing or decreasing?					
Quality and quantity of marine and freshwater wetlands	**No data**				Measures and data collection strategy proposed.
Is functional fish and wildlife habitat increasing or decreasing?					
Habitat inaccessible to salmon because of man-made barriers				X	Potential habitat not available to coho: 59% in Dungeness/Elwha; 73% in Quilcene and 39% in the Stillaguamish watersheds.
Is the area of contaminated sediments increasing or decreasing?					
Contaminated sediments				X	13,845 acres surveyed: 5,083 fail sediment quality standards and 3,173 acres do not meet cleanup screening levels.
Restored sediments				X	49 contaminated sites (total 2,197 acres) targeted for cleanup.
Are areas where shellfish can be safely harvested increasing or decreasing?					
Commercial harvest areas			X		Area safe harvest remains unchanged since 1989.
Recreational harvest areas			X		Initially classified in 1994, other areas have since have been classified.
Is water quality for recreation improving or declining?					
Bacterial contamination levels in rivers			X		Rivers are degraded due to fecal bacteria pollution, they haven't improved or declined since 1983.
Are toxins in the marine environment increasing or decreasing?					
Metal and organic contaminants in mussels		X			Concentrations of mercury, copper, zinc, PCBs, or butyl tin in mussels have declined significantly at six of seven long-term stations.
Occurrence of liver lesions in English sole	X				2 of 6 stations show increases of lesions, while 4 stations show no trend.
Are the size and frequency of oil spills increasing or decreasing?					
Number and volume of spills		X			80% of large spills are heavy oils from land based facilities and pipelines; 70% of medium spills are from vessel fueling operations.

Table 3. Data sources used to populate each performance measure.

Performance Measure	Data Source
Pacific herring populations and stock status	Washington Department of Fish and Wildlife, 1997
Salmon and steelhead stock status	Washington Department of Fish and Wildlife, Salmon And Steelhead Stock Inventory, 1992
Diving duck (scoter) populations	Puget Sound Ambient Monitoring Program: Washington Department of Fish and Wildlife, 1997
Harbor seal populations	Puget Sound Ambient Monitoring Program: Washington Department of Fish and Wildlife, 1997
Marine and freshwater wetland quality and quantity	No data
Inaccessible salmon habitat due to man-made barriers	Northwest Indian Fisheries Commission: Salmon and Steelhead Habitat Inventory and Assessment Program, 1998
Contaminated sediments	Washington Department of Ecology, 1997
Bacterial contamination of rivers	Puget Sound Ambient Monitoring Program: Washington Department of Ecology, 1997
Metal and organic contaminants in mussels	National Atmospheric and Oceanographic Administration, 1997
Occurrence of liver lesions in English sole	Puget Sound Ambient Monitoring Program: Washington Department of Fish and Wildlife, 1997
Number and volume of spills	Washington Department of Ecology, 1997

TABLE 4: Recommended performance measures for Puget Sound freshwater and marine wetlands and fish and wildlife habitat.

Performance Measures	Data Sources
Change in linear miles of salmon habitat inaccessible due to man-made barriers	Continue salmon and steelhead Habitat Inventory and Assessment Program.
Change in the area of key nearshore habitat: salt marsh; kelp and eelgrass beds	Develop and use new methods under Puget Sound Ambient Monitoring Program (PSAMP) nearshore habitat inventory.
Change in the health of intertidal habitat	Develop and use new methods under PSAMP nearshore habitat inventory.
Change in the biological health of Puget Sound rivers	Expand Ecology's biological ambient monitoring program to track change over time.
Change in the area of wetlands and riparian habitat	Develop a new system to detect change in wetlands and riparian habitat through satellite image analysis.
Change in the length of armored shoreline	Use existing Washington Department of Fish and Wildlife Coastal Spill Response Inventory.

Conclusions

1. Performance measure data are readily available. Puget Sound Water Quality Action Team agencies and other agencies, such as the Northwest Indian Fisheries Commission and the National Atmospheric and Oceanographic Administration, maintain long-term and reliable environmental monitoring data bases.
2. There is inadequate data to track the status and trends in the quality and quantity of fresh and marine water wetlands and fish and wildlife habitat in the Puget Sound basin. The Action Team support staff will continue to work with interested agencies, tribal governments and environmental interests to recommend measures and data collection strategies for fresh and marine water wetlands and fish and wildlife habitat.
3. The Action Team support staff will coordinate and integrate the development of fresh and marine water wetlands and fish and wildlife habitat measures with ongoing salmon protection and restoration efforts.

4. A long-term objective of this project is to improve the use of Puget Sound performance measures. Specifically, the goal is to improve their use for building constituencies, for educating citizens about the environment, and for setting priorities to target resource management programs on critical resource issues. In order to ensure this happens, performance measure data should be reviewed annually. Updated information should be reported in various formats, including the agency's web site.
5. Use and acceptability of the Action Team performance measures by the greater Puget Sound community will require coordination and ongoing effort. The Action Team plans to promote networking opportunities aimed at improving cooperation and coordination among various levels of government and the use of performance measures for public education and involvement.
6. The Action Team support staff will continue to investigate ways to improve the usefulness of Puget Sound performance measures to local and regional agencies and other interests.
7. The Action Team will continue to use performance measures to help set priorities and actions for each biennial work plan and budget proposal. The Team will continue to use trend information as a way to track effectiveness of the Puget Sound Plan in protecting and restoring the biological health and diversity of Puget Sound.

Protection and Restoration of Marine Life in the Inland Marine Waters of Washington State

James E. West
Washington Department of Fish and Wildlife

Abstract

The report from which this abstract is derived was commissioned by Washington's Transboundary Protect Marine Life Work Group as technical support for their development of an implementation plan for protecting and restoring stressed marine species in Washington's inland waters. The report gathers information from over 200 documents and interviews with over 50 experts.

This report (1) identifies thirteen species or species groups whose populations have experienced significant declines in population, or are suspected of being significantly stressed in Puget Sound; (2) evaluates anthropogenic and natural factors contributing to declines or stress; (3) evaluates current management strategies; and (4) recommends ways to improve protection and restoration of these species. The group considered in the report comprises three invertebrate species or groups, six fish species or groups, three seabird species, and one porpoise. Stressors discussed include harvest, habitat loss, pollution, disturbance, and climate-related variability. Potential and realized impacts of stressors are considered for all species' life stages. Unintended effects on the ecosystem from existing management activities (e.g., harvest and fishery enhancements) are discussed as well. Examples are drawn using known food-web relationships among manipulated species.

Recommendations for more effective restoration and protection are detailed and extensive, and include establishing marine refugia, continuing and increasing harvest restrictions, better protecting habitat, establishing a clearer link between habitat and natural productivity, identifying better the effects on organisms from exposure to pollutants, protecting sensitive species from disturbance, understanding better the natural climate-related cyclical nature of organism abundance, and recognizing the connectedness of all species in management schemes.

3A: The Health of the Puget Sound & Georgia Basin Ecosystem

Questions & Answers

Q: Can you explain what was measured as "shoreline alteration"?

Redman: The study was done by the Department of Natural Resources. I'm not sure exactly, but I think it includes physical alterations like bulkheads and piers. I can put you in touch with Department of Natural Resources staff if you want to know specifically what was included.

Comment: They have posters in the next room, don't they, that deal with that?

Redman: I'm not sure it contains that detail, though.

Q: You said there had been trends in PSAMP fish. Could you explain a little bit more about that?

Redman: I should have explained the acronym. PSAMP is Puget Sound Ambient Monitoring Program. Actually, Jim works in a group that looks at contaminants and contaminant effects in fish, and the Department of Ecology looks at contaminants in sediment. From those data sets, the Ambient Monitoring Program collected fish and sediments, we've seen no upward or downward trends in concentrations in Puget Sound over the period of 1989 through 1995 or 1996. PSAMP's fish sampling primarily relies on English sole for the long-term work.

Q: What percentage increase was seen in rates of liver lesions?

Redman: I don't have the data to answer that. However, in order for the difference to be statistically significant, I think it's probably got to be a pretty good number. I'd guess 20 percent or more difference over that time period. Jim?

West: But the overall levels in the Strait of Georgia were not high, but there was a trend. They were low levels but they were changing. Whereas in Elliott Bay, I think, the absolute values were much higher, so it's a little bit deceiving. Sandie is going to talk about that tomorrow in the effects of toxics session, so you might want to check that out.

Q: Where is the Strait of Georgia sample site?

West: It's in pretty deep water near the border, just south and west of Blaine.

Q: Kevin, you mentioned indicators of habitat for fish and wildlife.

Anderson: We've actually spent some time trying to identify what the parameters are – what the indicators are that we ought to be looking for. We made a proposal to the Puget Sound Action Team not too long ago and we were told to go back and work more closely with some of the salmon people that have been working on habitat issues. We've given it a good shot, but we haven't followed through and identified anything yet. What we have discovered is that we don't have enough information to adequately do some of these assessments.

Q: Kevin, what about indicators for wetlands?

Anderson: Well, there are two parts to wetlands. There's quantity and there's quality. There are pieces of information here and there, but consistently across the whole Puget Sound, it isn't enough information to provide an indicator. We find that we don't have an ongoing program to look at area – coverage. Landsat is one of the things we were looking at. And in terms of quality -- that's something that we have to work on in the future.

Q: [Unintelligible question for Bob Goodwin.]

Goodwin: It's a big debate. We could talk about regional equity. For example, Detroit absorbs all the externalities of producing automobiles for us in the Puget Sound who consume them. Isn't it fair that we should absorb some externalities in the production of transportation services for the benefit of those who live in the Midwest. I don't see a way, unless we radically alter our perceptions about what constitutes a good life and expectations about consumption, and what clothes we wear, and what we drive, and how we get to work. Without some absolutely drastic changes in those underlying cultural values, we're stuck with the messy, gritty industrial enterprises that produce that flow of goods and services. The best we can do, given that reality, which I can't see changing in the short run (and I don't think many people would want it to change in the short run), I don't see people voting for that. What we do is: we mitigate; we try to clean up at the edges; we use the police power to regulate what comes out of pipes and what goes into the air; and where we can, we try to exact some kind of public benefit out of those enterprises that are run for private profit, where it's appropriate, like many of the firms on Lake Union where you can get some public access and an amenity, and still have the flow of services. So I'm not sure that answers your question. I think it's a much broader issue that the whole of society has to grapple with, and frankly, I don't see that changing too quickly.

Q: Back in the 70's, we sort of figured that the natural environment belonged in the rural areas, out there, and that industry and development belonged in the urban areas. And when we felt we had to get something back in urban areas, we sought public access. Now we're finding there may be a shortage of habitat for these endangered species. Maybe instead of the old paradigm where we mitigated with public access so we can go look at the shoreline, we should think of trading off habitat restoration work and maybe we've got enough public access. Maybe some studies ought to be done for public access on the shorelines, and do some studies of habitat rebuilding, restoration on urban shorelines to see what we're getting back there.

A: Steve, you've raised some very good points, and I think if you look at major new activities that are being permitted in urban shorelines, like the Elliott Bay Marina, for example, the amount of effort, science investigation, and mitigation that went into that project was enormous. I'm not an expert in habitat values, but the consultant's report and monitoring indicated that there was a net increase in habitat value on that site as a result of the mitigation that went on for the project. Let me make another point. I was today reading a Sea Grant publication produced in 1975. It was quite prophetic in many respects and it coincided with the beginning of shoreline management in this state. One of the points made in this book was that we were looking at the rural shorelines as places to play and keep natural, and the urban shorelines as places for industry, jobs, and economic activity. The urban constituencies wanted to keep it that way. And maybe against the will of the rural constituents who would have loved to have had some of that economic development going on. Grays Harbor County, Pacific County, and so forth. I don't think anything's changed. I think the conclusions that they reached in 1975 are equally true today. So, the point that you're raising gets down to very fundamental, societal values, and those shift rather slowly, I think.

PUGET SOUND RESEARCH '98

SESSION 3C

COMMUNICATING ENVIRONMENTAL SCIENCE

Session Chair:

David Sale
Puget Sound Water Quality Action Team

3C: Communicating Environmental Science

David Sale, Puget Sound Water Quality Action Team: The idea of this session is to highlight some issues that come up when we try to communicate scientific information to the public. And trying to go both ways with it, to get the information communicated to scientists. When we first started putting the session together, we had a conference call that really took off. It was a nice open dialogue. We decided that we should try to accomplish the same during this session. Each person will come up and introduce himself, and will have about five minutes here to talk about some issues that are important from their perspective. Then we're going to shift to an open dialogue.

Ross Anderson, Seattle Times: I never dreamed I'd be sitting in front of a bunch of scientists trying to pass on wisdom. I mean, reporters, we make our living, more often than not, sitting in the back of the room sipping somebody else's coffee making fun of the people sitting up here. And that includes an occasional conference of scientists. It was a very strange idea, coming down here, but excellent.

I'm a classic example of a journalist who went to college in the late 1960's. I've never darkened the door of a biology class. I went to school when social sciences ruled the day, and we were all going to save the world with social science and politics and, of course, journalism. Natural sciences were pretty far afield.

I've been at the Times 25 years and I've written mostly about politics. But you don't write about politics in the Northwest, of course, without writing about natural resources. So I find myself at conferences like this, sitting in the back, sipping somebody else's coffee, and making fun of the people who are up here, trying to understand what's going on.

So that's how I ended up, last year, at the AAAS conference. I was sort of vaguely aware that AAAS existed, but then as I learned more about it, I realized that it was an extraordinary opportunity. So I ended up spending most of the week roaming, this wonderful freedom, I'd roam from one session to the next. Of course, didn't understand a whole lot of what was going on.

But one of the things I was fascinated with was this curious relationship between science and journalism. I remember writing about it at the time, and referring to journalists trying to find something newsworthy that could be translated into a newspaper, or radio, or TV story. It's a very curious relationship between science and journalism. It's one that fascinates me.

I've decided in the last few years that in my next life, I want to come back as a marine biologist, and not a journalist. It's also a volatile relationship, obviously.

Scientists distrust journalists because they believe, quite correctly, that we have very little understanding for what they do, or what you all do and how you do it. And that your work tends to get fractured in the re-telling. And journalists, by the same token, are sort of equally wary of scientists because we suspect, with good reason, that you all spend many, many years in graduate school learning how to obfuscate the English language, and torture it in the process. But yet, public policy these days is increasingly based on some combination of good science and good journalism. So we kind of need each other, which is why, I assume, we're all here.

The fascinating thing is that, I think, we are all in the same business. If you peel away everything else, we're all in the business of trying to increase the understanding of the human race about the world that it lives in. This is obviously a noble undertaking for which we feel, sort of, equally under appreciated and underpaid. But similarities all end there. I'm going to indulge in some sweeping generalizations in trying to compare what we do for a living. While, in this dogged pursuit of truth, we ask different questions.

Scientists ask what is this and how does it work, and journalists ask so what, why does it matter, why is this important? Which gets us both in trouble, especially when we deal with issues such as risk assessment. We have a tendency, in my business, to take important but incremental research on a potential carcinogen and turn it into a

cure for cancer. And we do it all the time. It drives you crazy, and I don't blame you.

Another difference; scientists are specialists. You guys know a lot about a few things. Journalists tend to be generalists who know very little about a lot of things. Scientists tend to work for government. Most reporters don't work for government and, in fact, we see our role, in part, as sort of a monitor of government. So when we deal with scientists, there is almost this, sort of, almost unconscious impulse to look for some way that you guys are wasting tax dollars.

I think the most important difference is the way we go about that search for truth. We go by entirely different rules and disciplines. Scientists' conclusions are drawn from data and derived from repeated experiments. Right? I don't understand them but I know that's roughly how you do it. Your bible is the scientific method; an orderly process of inquiry that requires precision and testing of hypotheses, and so forth. Reporters, our scripture is the democratic process; especially the first amendment. We value freedom of speech and an open exchange, which has nothing to do with precision. We value our constitutional right to be dead wrong about something. We mix science with politics, and economics, and business, and sports. We try to track the flow of money, and we love to speculate about why people do what they do. I have a lot of friends who are scientists, and I try to explain this, and they find it highly amusing. We believe the truth emerges from the conflict of ideas. If we depict both sides of an issue, somehow, in some mysterious, magical way, truth will emerge. This, of course, has nothing to do with what scientists do for a living.

But maybe the most important difference between what we do is, obviously, that journalists are communicators. We believe that knowledge and ideas are valuable only to the extent that they are communicated. To do that, we resort to things like storytelling and anecdotal evidence that, of course, is not evidence at all. That's another thing that drives my friends crazy. To us, if something that is lost in the re-telling. It's too bad. We did our best.

Scientists are into knowledge for knowledge sake, and, most times, my friends tend to be loners. They work alone. They conduct their experiments alone, and sort of occasionally submit their findings to other scientists for peer review; usually in a language that is unintelligible to anybody else.

An example to me is, Puget Sound marine science, I never darkened the door of a biology classroom, but I've written about it enough, so I probably know a little bit more about marine science than most people walking the streets. And yet, I spent some time in the poster session out here, and I would say that three-fourths of those posters, I don't understand, what we're talking about. I think this is the problem for science. For starters, it feeds the purpose for those people who shall remain anonymous that argue that government already spends too much money on pointy-headed scientists, that science should do that in the private sector.

An example, I write about fisheries a lot. I'm fascinated with them, mostly with the culture of fisheries and the process of that. I have indulged, now and then, in the science. And I remember, some years ago, going up to NMFS out at Sand Point to talk to a scientist, who will remain anonymous, who some of you may know, and who had done some work that basically argued that the way to preserve pollock in the north Pacific was to catch more pollock. I found this absolutely intriguing. I read a little bit of his stuff, but mostly I had heard through the grapevine. I called him up and it took me weeks and weeks to talk him into letting me come out to talk to him. So I went out and talked to him. He was a delightful character. He reminded me of the chef on the Muppets. I could've sworn he had a chef's hat, and he was brilliant. But for about a half an hour he'd talk, I was sitting in this little cubbyhole of an room and this is one of those biologists that does all of his work at this computer monitor, right? And he had his model and he was trying to explain to me how this worked. And I was getting frustrated because I didn't understand. He was getting frustrated because, Mr. Anderson, you don't understand that pollock eat pollock. And I was like, why didn't you tell me that first? They're cannibals? He says Mr. Anderson, I've been trying to tell you that for half an hour. I wish he'd have just explained that at the outset. I mean, I understood that. I can understand how this is a problem.

Now the flip side of that, I suspect that many of you, most of you probably know Don (?). Don was a

reporter's dream. He died about a year ago, and I miss him desperately. But Don was that rare case of a scientist who, in addition to fisheries science, understood politics. He understood economics. He understood and he appreciated and he spoke English. So I would run these questions that I couldn't resolve with anybody else, and he would sort of patiently explain it to me.

I'm going to give you one more example. I don't' know how many of you are familiar, or worked with Ray Troll, the Alaska artist. The salmon guy. "Spawn till you die." "Tankers from hell." He's best known, unfortunately, for his T-shirts because his T-shirts sell remarkably well, and he's made a lot of money off T-shirts.

Troll is sort of half artist and half scientist, and his true love, his true passion, is paleontology. He loves fossils, and he and a guy by the name of Brad Mattson collaborated on a wonderful book called Planet Ocean. And it's a book about paleontology of the oceans. After the book, which was wonderfully illustrated with Ray Troll drawings to support [it], afterwards they had a one of a kind exhibit at the Burke Museum in which they had the Ray Troll drawings of these wonderful, ancient, prehistoric creatures. And then examples of the fossil evidence that sort of suggested those creatures.

The interesting thing is how he arrived at those drawings. I did a column about it at the time, and basically the way that they got there, he drew these wonderful saber-toothed salmon, just these wonderful, fanciful creatures. But the problem was that none of the paleontologists would draw them. There were, of course, no pictures, and apparently the fossil evidence is all fragmentary. And so what Ray would do is he'd sit down with these guys, take a look at the fossil evidence, and, you know, draw as best he could. And then he's take it to these scientists, to these paleontologists and say, this is what it looked like. They'd say, no, it's not like that. He'd say OK, and he'd go back and he'd draw it again, and bring it to the paleontologists and say, is this what it looked like. And they'd say, no, that's not it. Try again. And then, that's it, you've got it, but don't you ever tell anybody I told you so.

This is sort of the journalists' version of peer review, but it worked. I think, perhaps, somewhere in there, there's a model for how your profession and my profession could make things work a little bit. Reporters are, I think, are obligated to improve our understanding of how you work, and our understanding of the discipline, of the science, of statistics and of risk assessment, and what is the risk, and what ain't. We can't continue to use ignorance as a fence. We need to resist that impulse to turn incremental advances in scientific knowledge into journalistic touchdowns. But scientists are equally obligated to resist their impulse to hibernate, to operate behind closed doors. They need to learn the basic communication skills that everybody else in the world has to abide by, beginning with the use of the English language. For all our "cure for cancer" stories, scientists are equally guilty of poor risk management when they use the risk of miscommunication as the rationale for not communicating at all. Thanks.

Bruce Brown, Independent Journalist: Greetings, my name is Bruce Brown. I am here for a variety of reasons. I am the author a book called Mountain and Clouds: A Search for the Wild Salmon. I wrote the scripts for a PBS TV series called *The Miracle Planet.* This doesn't really have bearing on what we're talking about this evening, but I am, among other things, the author of Mr. Wacko's Guide to Slow-Pitch Softball and creator of Mr. Pizza, of which we will say no more. But I am also, in my current incarnations, the owner and publisher of an electronic publishing firm which is probably best known for a web publication called Bug Net.

In some of the facets of my professional existence up to this point, I had an opportunity to try my hand and to wrestle with some of the challenges which I think are the fundamental subject we are talking about here, and which, perhaps, could be stated as the need to communicate important information that may be somewhat complex. That which may be beyond what can be easily stated in a simple declarative sentence, and yet has real bearing on people's lives. And one of the things that has occurred to me incrementally over the years that I have wrestled with this creature in the mud, and one media and another is that the medium is the message. A cliché perhaps, but as with many clichés, one that perhaps contains a kernel of truth.

As I have tried to skin a cat from one side and another, a bad pun or metaphor I'm sure perhaps in this group, but as I have basically approached the issue of communicating scientific information, information which has a

strong scientific aspect, to people in the general community I have become increasingly convinced that the medium that is employed at any given time really has a significant effect on what you can say. In other words, it shapes your message to a significant degree. I don't have the time and I wouldn't impose upon you, or presume to take the time that would perhaps be required to march through each chapter of my checkered past, and perhaps extract a kernel or the aspect of it which may pertain. But I'd like to tell you a couple of stories, if I could, from one or two facets of my professional involvement with this undertaking.

I think off the top of TV script writing, which is a lot of fun in a way. I mean you get to spend weeks, months, years playing with high tech gear and watching pictures go back and forth and listening to your own words be read, studied, and ripped apart at times. But it's ultimately staged in a lavish fashion, and it's real neat for all the reasons that television is a powerful medium. You see the glitzy surface that can be applied. I've found myself, as a newspaper reporter, first and foremost, a journalist, basically, as I saw myself, and subsequently, as a book author, somewhat surprised by the way television shaped the message that we were trying to communicate. And in *The Miracle Planet*, which was actually one of the most popular series that PBS has ever done, being viewed probably somewhere in the world right now, kind of like Stairway to Heaven. Somewhere in the world at any time, translated into seven languages.

As we got into [the making of *The Miracle Planet*], we found that sometimes things didn't really quite work out like we expected. For instance, it's all verbal. And you say, well of course it's all verbal, Bruce, in terms of cognitive communication, except for what you can do with images. But when I say it's all verbal, what I mean is, it all exists in the moment. You can't flip back and refer to a table. You can't go to the page before and refresh you memory on the definition of paleontology. You have to be able to hold it in the moment and you have to be able to understand it and deal with it comfortably in its totality in the moment, and make the references that are required with the idea in the moment. These requirements are more difficult than you might expect.

Then there is simply the limitation of the spoken language, which is of course a wonderful thing, but then we have inherent in it certain limitations. I remember, we went through maybe the fourth draft with a reference in one of the shows to the "rebooladooble" plateau. I have to say parenthetically here by way of explanation, *The Miracle Planet* was KCTS first big play in the national stage, and there was a lot of subtext and some ego of various people who shall remain nameless. One of the things they had done was essentially to license from Nippon Television a whole lot of gorgeous footage. And so they had this store, and they had for the basis for what became *The Miracle Planet*, a Japanese television series that dealt with somewhat the same subject. And so we were handed these scripts, and translations from the Japanese, as the first phase in producing what became six one-hour shows for American PBS, and eventually translated into every language but Japanese. So through four drafts from what had begun with the Japanese translation of the basis material, we're hearing this thing about the "rebooladooble" plateau and finally someone said, because the fact checkers were always combing, "What is this 'rebooladooble' plateau thing"? And so the various reference books were consulted and so then the question of spelling was raised, and finally, Nippon television was queried on this aspect of the script. And it turned out that it was a Japanese mispronunciation with the stereotypic confusion of l's and r's for Labrador. What they were trying to say was Labrador, and yes this made sense, great Canadian shield, you know. And we're talking about, you know we have a geologic reference point now, you know, and it made sense. But existing exclusively as a verbal form of communication, you know, it had a kind of an inadvertent problem that took a long time to work out.

Another thing that struck me was something I never would have thought of before I had to write words to put into someone else's mouth, what you know the writer thinks of as the talking head, a lesser form of life. Animated only by my brilliant prose, but it doesn't really quite work that way because this guy is, you know, he's the star. Welcome to the party, Bruce. This guy, he's the one they brought in, at huge expense from New York. And the fact that he doesn't know—well, some attitude is showing through here—but the fact that they decked this dude out, who again, shall remain nameless, expect everybody knows him and if you've ever seen *The Miracle Planet*, you know who I'm talking about. They deck him out in your REI down vest and I think they even got him a pair of jeans, you know, a real outdoorsy touch, and they positioned him in front of various scenic backdrops. The guy, and this had nothing to do with the fact that he was from the East Coast and his experience was very good, and I

don't mean to put him down, but it turns out that the guy, big, huge name that he was, had a limitation in his delivery that I had never even thought of. The guy had the ability to move on only one emotional progression. He could only follow an emotional or a vocal progression down. He had no way to take something up to a climax.

The natural flow of language, actually spoken language as I am speaking to you now, it rises and falls, and the ability to hit a rising sequence or progression of ideas and to carry it with your voice and with the cognitive element is very useful in human communication. And if you strip that out, it's really very weird, especially for the author who goes back scratching his head going how can I write this all in descending emotions. How can I do this. It's not that easy, frankly, but it must be done because the medium must be served. And so we do these things, and nobody knows anything about it except, perhaps, the more intelligent and questioning and thoughtful of the audience there at three in the morning will wonder why it was done that way. The reason it was done that way, in part, had nothing to do with the science, although the science is crucial. It had nothing to do with a lot of things that would be obvious. It was, in part, formed by the vessel in which it resides, the medium being television. In this case, a key limitation was the talking head who was crucial to way the narrative was structured.

I could tell you stories of similar nature with regard to daily newspaper journalism, which is an art that Ross and I have practiced together. In fact, a small admission here, I hope Ross will not flog me for this later, but he and I go back to the Seattle Times in the late 1960s, and were reporters together, and so this is what happens. You start out as Jimmy Olson and you end up like this.

At any rate, I have practiced that craft, and it is a real art, and it's wonderfully refined. It's like a stone you pick up off the beach that has been smoothed by, in this case, practiced hands and honed for the purpose of communicating news; communicating information in an extremely efficient, honed down fashion. And for news, for new information of the sort you get in a daily newspaper, and on the TV and radio to an extent, is a wonderful thing, but its limitation is the depth of ideas that can be communicated.

I launched into my first book, Mountains and Clouds, primarily because I was covering the Boldt decision, which was the popular handle on what became the salmon crisis that never ends, for the PI. I had this feeling developing over a couple of years that there was really something very important here that couldn't be approached in daily newspaper stories. I mean I was writing daily stories and they were getting good play and having good fun and, you know, afflictingly comfortable and comfortably afflicted; all those things that get reporters going. But I had the feeling that I was never able to get at the core or the root of the story that really needed to be told. The relationships, the complex relationships of politics and public policy and natural resources and resource exploiting industries and the way they were working and they way they were shaping our lives and making the world that our children would come to live in. You could get at the firecracker going off. You could capture that pop and explosion of the moment, but putting that firecracker in a broader context was very difficult. So in that case, the vessel into which the information was poured to a significant degree for me, shaped the form of communication that came out of it.

The same is true of books. The strengths and weaknesses are different. The same is true for the web, where I now publish a journal that deals with this aspect of scientific inquiry and an effort to communicate it to a wider audience.

I would say in conclusion that the challenge is very similar across the various mediums even though the demands of the medium may be different. As a communicator, a person who makes building blocks of understanding accessible to people, my fundamental challenge is to create compelling narrative; to tell the story in a way which touches the people who are exposed to it. And the tools and the way you approach it will differ, just as the story will differ from medium to medium. But to me the challenge is fundamentally the same, and frankly this may be part of me still rebelling against my parents, to tell you the truth.

My father was, for many years, a professor at the University of Washington. His specialty was Irish literature. He was the guy that everybody took classes on James Joyce from, you know. And my father specialized in a writer for whom the idea that the writer, the communicator has a responsibility to meet the reader halfway

and to draw them in, was heresy. My father, you know, lived in a world where the writer existed on a higher plane and it was your job to haul yourself up to the top of the mountain. You could take a class from him and he would get you up there.

I don't, as a professional communicator, subscribe to that philosophy because, frankly, I think the ideas that we're dealing with here, the things that we're kicking around, and I and my colleagues have come here to share our thoughts with you about really matter. And they matter so much that they can't be left to the stray traveler who may stumble into the room and into some understanding or exposure. What we're dealing with matters so much that it must be communicated in a fashion that does justice to the ideas and allows people to make the right decisions.

You scratch a journalist and they start talking first amendment and they start talking journalism, but, you know, I really believe and second what Ross was saying. I believe in the multiplicity of voices. I believe that, for democracy to work, you have to put the tools in the hands of the public that will enable them to make good and reasonable decisions. And for that reason, our job, my job as I can see, that as a communicator, as a script writer, as a journalist, as an author, as a publisher, is to get that information in a form which is animated by narrative, which compels people, which communicates in a significant fashion and basically, makes this whole system work. That's, in a nutshell, what I try to do. To the extent that I may have succeeded at one small moment or another, this is what I think, I hope I may have succeeded at. So, I look forward to hearing from our colleagues, and I thank you for giving me a moment of your time.

Keith Seinfeld, KPLU-FM: I have a lot less experience than either Ross or Bruce, so I may not have as many stories to tell you. I've been doing this for about five years before I became a reporter.

I guess I should tell you what I do first, some of you may not know who I am. I cover the environment at KPLU Radio, which is one of the two National Public Radio stations here in western Washington. I've been doing that for about a year and a half, and before that I kind of hacked around between Seattle Times and Tacoma News Tribune and Seattle Weekly and some other local publications, and before that I was a high school English teacher.

Like Ross and Bruce, I do what I do partly because I actually enjoy the complexity of the type of the work that you people are doing. And we all sort of struggle against the language that you do it in, as Ross so articulately pointed out. We struggle against that, but we enjoy the struggle, ultimately, because we're interested in taking things that are complex and trying to put them into narratives and put them into language that a wide portion of the public can understand.

As a radio reporter – Bruce mentioned the limitations of television – you're one step further limited in that you don't have any visuals whatsoever. One of the first lessons that goes with any print reporter that wants to go into radio—there are a few of those at National Public Radio—is that you learn that you only get to say things once, and your listener is not a reader who can go back and check on, as he said, a definition or phrase, a location or a description. They only get it once, and so the crafting of those words becomes even more important. You're sentences become shorter. You stick with declarative sentences and you have to weed out a lot of the complexity that you enjoyed sifting through in the first place. And that can be really frustrating later on if you talk to one of the scientists you interviewed on a story and they generally liked the overall presentation, but, you know, there's a lot of things that didn't make it in there. Maybe there are some subtleties that didn't make it in there or just specific things that had to get cut out because there's only so much you can communicate in a few minutes of story.

Fortunately at NPR, we have room to go five or seven minutes, occasionally, on a story. That seems like a long story when you're a listener, but if you printed that out, it wouldn't be as long as any feature story in the newspaper. And our standard stories, the ones you most often hear, even on NPR, our local newscasts are anywhere from 60 seconds to three minutes. That works out to about anywhere from three paragraphs to maybe eight or nine paragraphs. Think of what you can say in simple declarative sentences in that much time, and you see the challenge we're wrestling with.

So, while your task is to go into detail and document and as many steps as possible, we have to take that stack that you created and shrink it down into something much, much simpler, which is why we're so grateful when we find someone who can just say, the big fish eat the little fish. It makes our job a lot simpler.

I thought maybe I'd talk a little bit about some of the questions I get from scientists occasionally and a little bit about what it's like being a reporter. At KPLU, we have a fair amount of freedom, but at the same time, we're responsible for producing, usually, about three stories a week. And that's pretty common at a lot of newspapers also. Sometimes some reporters have to put out stories five days a week, but three to five days a week is not unusual, unless until you get to the ranks of being a senior reporter where you can work on long projects and stuff like that.

If you're producing three pieces in a week, you don't have a lot of time to do tons and tons of research and to talk to the seven or eight different people who have studied different aspects of the salmon life cycle. You know, you've got to get a couple of experts and hope that they can speak about their area of expertise, but also, speak a little bit more broadly about the field. That's one of the frustrations that reporters run into a lot—that scientists are specialists. They feel very comfortable discussing whatever they have published on, but if you get beyond what they've published, they're less comfortable. If you broaden out to what the colleagues on the same floor of the building are doing, they're uncomfortable, and they don't want to say anything. And we need people who are willing to say, here is where I am in the spectrum and here is the general spectrum and here is the terrain that you're trying to navigate. They are rare. I'm saying that to encourage you, when you get a call from a reporter, to keep that in mind. That more often than not, that's part of what we're looking for. Let me give you an example of some of the topics I've covered just in the last couple of months. I have selected out only marine-related topics, by the way. Covering the environment covers a lot of issues beyond marine issues.

Marine issues I have covered include sewage overflows, which are discussed in this conference; oil tankers and oil pipelines and the relationship between them and oil spills; new EPA regulations about chlorine dioxide and how they effect pulp mills. In this story I've had to address "what is chlorine dioxide anyway?" and "why is it different from other forms of chlorine?" It is a challenge to sort that out, where you have some activists that say all forms of chlorine are bad or some forms are bad and others who say otherwise.

In Puget Sound, I've also covered the state of the bottom fish—"what do we now about them?" and "what don't we know?" and "what should we know?" and "what do we wish we knew?" I've also covered herring populations—"what is going on at Cherry Point?" and "is that important or is it not important?" and "if it is important, how important is it?"

I've also reported on something called TMDLs, and I always have to stop and try to remember what that stands for —the Department of Ecology and some other agencies, I suppose, are supposed to figure out what daily load of different toxic components can go into any body of water. This involves analysis of dilution, which is another thing we have to deal with sometimes when we're writing about Superfund sites and cleanups.

I did a feature story on salmon farms. That was one where I talked to a whole lot of scientists, including a few who are here, not in this room, at this conference, and boy that was frustrating. A classic issue where it's not even as nearly as complicated as dilution zones or chlorine compounds, I don't have to get into chemistry, at least, which is for me, the hardest of all the sciences to get into. But to get any sense of what really are the dangers of farmed Atlantic salmon in Puget Sound in terms of diseases or genetics or the feed that they produce and what antibotics that may be floating in the water or dropping down to the bottom. Get a handle on that well enough to be able to come back and write a story. Again, come back from all that research and, where's the narrative? A narrative is a story with a beginning and a middle and an end. It's got a character or two in it that we can identify with. It has some personality. Well how do you get from ten different experts' evaluations of farmed Atlantic salmon plus a few activists who are against them plus a few businessmen who are trying to make a few pennies off of selling them. How do you get from that into narrative? That's the real struggle that we deal with.

Brown: Not to interrupt, but I think what you've touched on is really what the journalist struggles with, but

I have the feeling that many in the wider population never know that struggle goes on. They think the narrative just pops right in there. I mean you just sit down until blood appears at the temples and the story writes itself. This is what reporters admire among each other: the ability to reach into that squirming mess and pull out the narrative and make a story out of it. But I think that a lot of people never realize that that's the challenge to many of us, to agree.

Seinfeld: That's the craft and the art, and the masters are the ones who can go in and find a narrative line that will tie the most obscure thing, the most obscure topic into something fascinating where, in a newspaper, where you'll actually turn to page 12 and follow the jump. That's the test. And in radio, where you can at least impress an editor long enough that he decides to let you have five or seven minutes to talk about it, and I tell you, when you mention salmon these days, you'd think there would be a lot of interest, but it's the other way around. People, certainly editors, feel like they've been over-saturated and they're really suspicious of any salmon stories.

One thing scientists often ask is "why was this a story but not this other thing"? I don't understand. Why was this type of research, why did that make it into the news and something else didn't. And that's one of those areas where you're getting into why journalists sometimes occasionally consider themselves members of a profession, because there actually is a body of knowledge that you learn through experience, and you learn through trial and error, and you learn through studying. And what makes a news story is one of those things that kind of separates people who can keep succeeding in this business and those who can't. It's being able to recognize a story. So it's not something I can tell you right off, what the difference is, but some of the most obvious things are timing, how fresh and new is the research. In some sense, is this something we haven't heard before or is it related to something else that may be in the news? Or maybe was in the news recently and people are concerned about it? And if you're wondering if something you're studying or something you've been looking into might be newsworthy, the most basic test I've ever been able to give people is, can it hold someone's attention at the dinner table. And someone who is not a scientist, for somebody who is completely out of the scientific field, can it hold their attention? What part of it does hold their attention? That'll tell you what's going to be of interest to a journalist more often than not.

When I call up a scientist or when I meet a scientist, I tend to, from the outset, respect that this person knows what they're talking about, at least within their field. You know, I don't spend a lot of time checking credentials, you want to know that those are there, but otherwise, you now, that's not the type of reporting I'm doing where I'm actually investigating the scientists.

The flip side might be useful for you to keep in mind. By and large, we do know what a story is, and we do have reasons why we're asking the questions that we're asking and doing the story that we're doing, and that's part of a two way street, I guess.

One thing you should notice that, one of the best things about doing environmental reporting and scientific reporting on Puget Sound is that most of you, or a lot of you, end up doing a lot of field research. And we love going out on field research, because we like to get out of the office too. It's one of my favorite things. So that's kind of a few rambling thoughts. I'm really curious to hear what kind of questions you have and I'm really curious to hear what Richard has to say.

Richard Strickland, University of Washington: I guess I was added to this panel too late to be printed in the program. I think Dave was worried that if he put these three journalists here, they'd start devouring each other, so he thought he'd have a scientist here as a punching bag instead. But I'm actually not a real scientist, I just play one in front of students. I started out and got an advanced degree in Oceanography and never made it to my Ph.D. I wound up writing a book instead which some of you have heard of and Ross referred to earlier in the evening about Puget Sound.

From there I've basically been a writer and teacher. I don't do real research, although I can understand most of what's said here today, even some of those posters are a little over my head, so don't feel bad. I even did an internship, actually it was a fellowship, that's a little more prestigious, at a TV station once that was sponsored by the American Association

for the Advancement of Science. I spent the summer of 1985 at the leading TV station in Miami, Florida, of all things, where science news is mainly geriatric medicine and emergency room trauma. I was there the summer of Miami Vice and the summer when, if you went too slowly on the on-ramp or the off-ramp to the freeway, there would be a young man with a big chuck of concrete to put through your windshield and then snatch your wallet or your briefcase or your purse, or whatever. So it was very educational for me to see what goes on inside a real, at least a broadcast newsroom in the spot-news capital of the United States, which they called themselves.

After that I spent six years as the science writer for the Washington Sea Grant Program, some of you may know about that program. I acted then and I still act quite a bit as a liaison between real scientists and people like these. I also teach freshman Oceanography at the University of Washington. Again, I'll go and listen to the research seminars and read the research papers and then digest that and spit it out at a level that freshman level non-science majors are expected to be able to at least get a "C" on, which I enjoy. I like being right in the middle between the "real scientists' and the "real journalists" and the journalists all see me as a scientist, and the scientists all see me as a journalist, so I turn my coat inside out and be whatever I want to be.

I brought my red pen up to the podium because I'm going to put on my teacher hat for a moment. I've had this clipping from the Seattle Times on February 16, 1997 with this young man's (Anderson's) picture on my bulletin board now for 13 months. I give it a "B." It's substantially correct, but it needs to be corrected in certain aspects.

To scientists, truth is determined only by data derived from experiments. Findings are tentative and qualified. They don't believe there is a last word on anything, correct. Reporters' scripture is the first amendment and the value of freedom of speech.

Correct! However the implication that there is conflict there I will mark incorrect, and will elaborate.

We believe truth can emerge from conflict. If you pick both sides on an issue, truth will ultimately win out. This is a concept that baffles most scientists.

Big red X. This is not an example of a true scientific meeting.

Anderson: I think what it says is that it "amuses most scientists."

Strickland: You may recall it, but here it says "baffles." If you go to a real meeting of specialists at the top ranks of research, you will find that the process of conflict is integral to science, actually. People will present one view. People will present an opposing view. They'll haggle it out. There'll be a stream of conflicting papers, and somewhere down the line, some people will win over more adherents than the others and one theory will come out on top.... This is a science lesson, I'm afraid, because I have to ask you, "Can I see your data? What's your sample size?"

Anderson: It consists of one guy in a small room out at NMFS.

Strickland: I think I know the gentlemen.

Anderson: That's enough of a data sample for a journalist. "Anonymous source." In fact that's a rather large sample.

Strickland: I can see why you chose that profession. You are entitled to this view point, but a scientist I would qualify this statement by saying, "in my experience," or "I have a feeling that." The essence of science is not to dismiss the mystical or the intuitive or whatever, but to properly label it as such and then to have a separate logical process that can be understood by anybody in which you assemble evidence. You weigh it. You present conflicting explanations. You weigh those, and so forth. There is a stereotype of a scientist as a loner, but I really have to call it a stereotype because, in my experience, oceanography (for example) is getting to be more and more of a group science. You have to go out on a research vessel. A research vessel costs upwards of $20,000 a day to operate and the problems are so big that no one person can attack it solo. It's

not like Thomas Edison with his light bulb in his lab, or whatever, anymore, and I suspect that most sciences are that way now too. Genetic research, etc. People have to cooperate and those that are not able to cooperate are very quickly shunted off to the sidelines, the cold fusion arenas of science.

There was a little e-mail exchange prior to this meeting, and I'm being pretty much responsive. I'm not so much contributing my own stuff as reacting to things other people say, but I wanted to defend scientists on two grounds. Number one: the right to be complex and specialized. That's really the only way that science has advanced, and the farther we go, the more that's true. And the right of the scientist not to comment or not to form a judgment, even though the press may want one. I'll give two examples, just in the last 24 or 36 hours. We've had our own research vessel from my own department go out on Lake Washington and shoot off some air guns, to see that the air guns worked before they take them out on Puget Sound to look for earthquake faults. I think everybody would like to know where those are and when they are likely to go off and how severely and so forth. So later some people reported some dead fish floating in the lake, and to its credit, the Seattle Times headline was something to the effect of, "Fish killed found in lake after air gun testing." In other words, they didn't say air guns kill fish. That would not have been a scientific conclusion. They restrained themselves from that, but no scientists would want to jump the gun and prejudge that one way or the other, as tempting as it might be for journalistic reasons. There are all sorts of possible alternative explanations. There are all sorts of evidence that could be gathered before having to draw that conclusion.

I want to give another example: the asteroid. Yesterday at this time an asteroid was going to come within 26,000 miles of the earth in the year 2028, they know the day, October 26th or 16th, and you know their calculations were a little shaky and it might hit the earth. That's pretty close. That's closer than some of the geosynchronous communication satellites that send our cable TV back and forth. Today, it's 600,000 miles. They went back to 1990 photos, found the asteroid in places where they hadn't seen it, and recalculated the trajectory. Now it's going to be twice as far away as the moon. So you don't want to really jump to conclusions if you can help it, much as the headline that an asteroid is coming is valid, but to say what it's going to do would have been very premature, and probably still is fairly premature.

So scientists live and die, basically, on accuracy. Journalists live and die on selling newspapers or attracting listeners to their station, whatever. And those two can come into conflict, I agree. I'll also agree that the better the scientists can communicate what they're doing and how they're doing it and so forth, the better. There's no defense of scientists being poor communicators, although you can't expect every scientist to be a good communicator any more that you can expect every journalist to be a good scientist. They are different specialties.

I want to draw an analogy to what journalists respect in certain other fields: confidentiality of information in certain circumstances. For example, the attorney-client privilege and the doctor-patient privilege. Now I know leaks are a very popular thing. They are unethical but they happen. But there is at least a principle that's established in both ethics and law about information remaining confidential under certain circumstances. And there is at least lip service given to respect for that. So I argue for recognition of that in the scientific arena. There's a scientific process called "peer review" in which a scientist makes a draft paper of a preliminary conclusion or something like that and, present company not necessarily accused, but I've heard criticism from the press types in the past that, well, you know, "This guy has written this paper so why is he sitting on it? Why can't we publish this? Somebody's trying to squelch information that public tax dollars paid for."

The process really is that a draft is just a draft and there is established hierarchy of review by which you first share this people that you're friends with, and ask them to tell you what they think is wrong with it or what are the good parts or so on. Then it gets sent to people whom you don't know, who may be your enemies, who are trying to get that research grant instead of you and they try and pick it apart. And only after it passes all those tests are you ready to stand behind what you're going to say to the public. Now some people are confident enough to say things before that, but I don't think it's the place of the press to be trying to tamper with that process and accuse scientists of greed or dishonesty or anything like that by keeping the review process confidential, by keeping findings confidential until they've gotten the proper scientific exchange of ideas to where then they are ready to go public

with that. Public agencies that conduct science are subject to slightly different constraints because of law about open information and so forth. But even then there's been a controversy with the public National Research Council, which is run by the National Academy of Sciences, when they try and come to conclusions about important scientific issues in the country. I believe that there has recently been a court decision that has forced them to open up their review process more to the public and the press than they previously had, which makes scientists very uncomfortable. Again, if you can't talk in a confidential fashion with your scientists about what do you think about this idea, do they think it's crazy, do you think it makes sense—if you're going to have to start tiptoeing around worrying that the walls have ears all the time, then that's going to compromise the scientific review process, which I think is unhealthy.

I think I've covered about everything that I wanted to here. I'll stop there and I may remember other things in the discussion. Thank you.

Q: Ross, you have no science background whatsoever? It seems like a really good idea to take an environmental science just at a general level to give you a good idea of the systems that are involved.

Anderson: I agree. My guess is that my lack of any formal education in natural sciences is worse than most of my colleagues. I worked at it. I struck a deal with a biology professor. I'd taken another course from him earlier, and he said he'd give me a "D" if I promised never to take another class from him. You're dead right. Now mind you, I consider my profession to be a year round never-ending graduate school. I mean, what I do is I go to school for a living.

I'm learning this evening. Richard's points are fascinating. Now that's going to enlighten me on marine biology, in terms of the ethics of science. I would love, and still plan to take a year off and go back to the UW. And I will do that. Of course, by then I will probably be retired.

Mearns: I work with NOAA and I've been involved in oil spills of the past ten years and wastewater treatment and sewage issues for the 15 or 20 years prior to that, and I guess what worries me from this conversation is I don't see how we are going to learn from the past. Is there a way that we can collectively analyze past situations where science and policy have clashed, resulted in a product, an action, that cost the public billions of dollars, in the future. For example, today we've been hearing about wastewater discharges and new outfalls, and so on, and Puget Sound modeling, and I haven't heard one word about what went on in the previous decade in the media and in the decision process. The decisions, as far as many scientists are concerned, were controlled by a few specific scientists that the media went to. In looking at the future, in the next two, three five years and so on, as these issues come back to the surface again, it seems to be there's no mechanism for going back and looking to see what we did and how we decided something in the past, so that we can build on that, at least in evaluating he issues again in the next decade.

I'm not sure I'm making myself clear, but scientists carry with them a long-term history in their field of what goes on, what the decisions were, how the data was used, how they build on a story over a five, or ten or twenty, or thirty year career. But they are dealing with the media in little chunks, episode of events and decisions and policy. Maybe you guys can help me define the problem.

Sale: If I could paraphrase Alan, I think there's a certainly continuity that you have when you work with something a lot that you know the past, you've followed a certain story and when a reporter picks up that story at one point they don't have that continuity.

Brown: You are speaking to something that is very real, and it is an institutional problem in the news media that extends beyond the coverage of scientific issues. I think for instance of Bruce Chapman. Bruce Chapman was a two-time a city councilman in the city of Seattle. He later went on to be a minor force in the Reagan administration, and came back to Seattle twenty years later, and there wasn't anyone on the desk of the daily newspapers who remembered that he was from Seattle. This sort of short term memory loss which is a function of, well, if Ross cares to he probably could speak more to the administrative and structural natures that produce this kind of thing. But you see it all over the place if you have any history in a town or a

discipline of study or an area of interest.

Actually, I was thinking of the issue of Atlantic salmon and the farming of Atlantic salmon in pens, essentially, in Puget Sound. I believe I wrote the first story on that subject in either of the major dailies in the city of Seattle. It was written in the mid-1970s, probably about 1975. There was nothing in the PI morgue on any of this when I went into it. I can't speak to the Times, but the PI was actually more aggressive on that subject at that time. And I would guess probably that the PI's morgue would also be reflected in the morgue at the Times. So, I'm just a reporter, a cog in the machine, a functionary doing my job. Well, I developed some knowledge on this subject. I have some history. I actually go back to the beginning, I would say, of the discussion of these issues in this community. Well, I haven't written on that subject in 20 years. And the reporters flow through. New people replace old people. The collective memory becomes diluted and I don't know what we do. This kind of wanders off into structural questions of journalism. Do you have any comment on that, Ross?

Anderson: It works both ways. I'm thinking of a conference on covering the oceans down at Scripps I attended about a year ago and it was a fascinating conference. It was about four or five days. It was sort of half scientists from Scripps and elsewhere and the other half of us were journalists. It was a terrific gig, but I think it was the first or second night we had a dinner right there at the campus and they served salmon. And everybody I was sitting at the table with – the environmental reporters form the LA Times and the New York Times and a couple of the oceanographers from Scripps – was remarking on the irony of serving an endangered species at a conference on oceanography. Well I tried to explain to these folks that yes, while we have serious problems with salmon in Puget Sound and the Columbia River that throughout most of the range of Pacific salmon the biggest problem is a glut. That there are too many; partly because of farms but partly because of, what is it, fourteen consecutive years of record runs in Alaska. There is too much salmon on the market. And prices have plummeted. Well I made my case for fifteen minutes or so, and at the end, nobody at the table was buying it, including the two oceanographers. I guess my point is, we all buy into, we all have sort of short memories, and buy into mythologies which journalists and scientists are equally obligated to try to dispel. But it's always going to be a tough bite. The myths are always bigger than the truth.

Q: I just want to speak to this point. I feel like an interloper like a journalist because I am an historian in training. I have to shuttle between reading past accounts in newspapers, particularly in Seattle newspapers before World War II which were notorious news publications and then shuttle back and forth between your reports and my own research in environment history. One of the problems: writing histories is a very good idea, but in my work in history of science and environmental history, I've often found that some of the narratives that I'm writing to try to frame the complexity of what the scientists do, are met with a great deal of hostility.

Brown: What kind of a narrative do you mean?

Q: I wrote an article about Lauren Donaldson and his research, and I basically, decided after a while that with the exception of the folks in fisheries, that there were certain people that were invested in the hatchery regime that Donaldson supported. And another friend of mine who is higher up on the food chain, he's now a professor, but basically he's provided the first comprehensive environmental history of Pacific salmon. And he's been able to conclusively demonstrate that there was widespread belief amongst scientists to support hatchery regimes. And the people, there was research as early as 1918 showing that hatcheries were ineffective and were damaging the stock.

Brown: In fact there was no concrete evidence to support that they had any positive effect, whatsoever.

Q: Yes, and that was suppressed by people like Spencer Baird and Bart (?). Well, when he presents this information in certain circles, he's met with a great deal of resistance. So I guess the question I'm posing to scientists and journalists alike, is when someone like me as an historian comes along and wants to destabilize these narratives and tell you the stories that creates a great deal of resistance. How are we supposed to communicate and then present our version and complexity to a general audience

when we're unseating positions a privileged scientist holds and also challenging journalists? As someone who does have the luxury of doing research provided there's a job out there, to tell a more complex story than you can on the op-ed page?

A: I'm reminded of two things. One is the movie *Viva Zapata*, with Marlon Brando, where he leads a revolution and then finds himself behind the dictator's desk with a young scruffy man, and he's saying to that young man, 'What's your name?' and then he suddenly realizes what he's done. He's become the establishment, and he is punishing the revolutionaries, and so he walks out. And there's also the book by Thomas Kuhn, "The Structure of Scientific Revolutions." The prevailing paradigms always become the establishment, and if you're a rebel, you had better expect a fight. I think it's an occupational hazard.

Brown: As an aside on Lauren Donaldson, I remember sitting in his office in the mid 1970s and raising, I had the feeling from the vehemence of his response, perhaps for the first time to his face, the idea that genetic diversity was an issue which, if examined in detail, at the very least introduces complexity into the hatchery picture and at the other end of the spectrum, identifies the fatal weakness of the hatchery paradigm. And Donaldson waved his hand and said, "There's plenty of diversity. We've got all the diversity we need." Speaking to the scientist and the obligation of the scientist, I will have to say, as a journalist who knew that Donaldson had also supported the plow share program which was never enacted but publicly planned and discussed. [An] idea to create a year round harbor in Alaska by detonating atomic bombs above the Arctic Circle. and Donaldson had signed off on this sucker. Knowing this, among other things about Loren, I came with skepticism and was prepared for a fight. And that's part of what Mountain and Clouds was about; exactly that struggle over that paradigm and the effort to raise the issues, to put the ball in play in public discussion.

Comment: Hopefully the scientific process is designed to overcome the individual scientist who may get hide bound in his of her beliefs that do not stand up to new paradigms.

Brown: Well, he was very successful. It's a double-edged sword. His success became his great weakness. It's human. It's the way we all are.

Strickland: I had a talk with him once about radioactivity. He was in the group that went down to the South Sea Islands after World War II to look at the impact of nuclear testing down there, and also was in a group looking at potential leakage of Hanford radiation into the Columbia, and actually there was some leakage earlier, and it's not over yet' I'm sure. He just said, "Hey, radioactivity is great. It never hurt me." All of his colleagues are dead and died fairly young of mysterious diseases, but he is still alive and so he can be reinforced in his own beliefs.

Brown: Lauren Donaldson was a real figure of some substance, and did some good. The thing is that we all strive to attain an ideal, and the ideal for the journalist may be in some ways substantively different from the scientist, although, I have been very interested in your comments. You've opened my eyes to some things that I hadn't really grasped. And I think maybe there are analogs there that I didn't perceive before, but none of us attains the ideal. You get up every day and you try to do the best you can and sometimes you do and sometimes you don't. We try to tell your story.

Q: This is just to follow up on the first question that was raised. As many of you may know, young scientists are having a harder time finding jobs than our predecessors, and I'm wondering, to the journalists, are people with masters degrees and Ph.D.s in science becoming journalists. Are you recruiting them actively? I'm not talking personally, but I just feel like that would be a great, I mean there are not enough jobs for all the young scientists that are being trained in all mediums right now.

Anderson: I think that it would be overstating to say that anybody's going out and recruiting scientists, but science journalism is one of the growth, I mean, journalism is very prone to fads. We went through the fad of business journalism during the 1980s and into the 1990s, and I think that's waning. And one of the emerging fads, which I think is wonderfully healthy, is science journalism. You look at the Tuesday science

section in the New York Times, which is considered to be a model in the industry now. When Bill Dietrich quit, we all wanted go out and slash our throats, and then Henderson took over, and picked it up extraordinarily fast and she's doing terrific work in my opinion. But are you going to be able to take a Ph.D. in chemistry and go to a newspaper and get a job? No. But one of the roots that a lot of scientists overlook is that, I can understand if I was a scientist why I would be reluctant to take five years of work and trust it to an ink-stained wretch such as myself to interpret to the rest of the world. I'd work pretty hard at it and probably do a reasonably good job, but there are other ways of doing it.

I've spent five years on the editorial page at the Times, and every day the Times runs at least one, usually two, op-ed pieces. We are desperate for good science on that page and several times I have been out to the UW and talked to brown bag sessions with faculty, trying to give faculty and students some clues as to how to write a decent op-ed. Because we get relatively few submissions, even though we're only a few blocks away from the UW, and those we do get are mostly unprintable. You read the piece, and you can tell that this is somebody who is very smart, somebody who has something important to say, but, darn it, isn't saying it. I've got a one page lists of do's and don'ts about how to do an op-ed. Now does that mean one can do it? Not necessarily, but if one just follows a few simple rules, the op-ed page is a great way to get your message into the newspaper. And I thing that similar devices exist elsewhere without going through the filter of a reporter.

Q: So you're saying that scientists are welcome to write good articles and they are likely to get published first.

Brown: My take on that is that, one of the curious things about journalism is that it is, in a way, open to all. You can get a journalism degree, but you sure don't have to have one. You can get no degree at all. One of the things that's very egalitarian, and I think refreshingly so, about the journalistic profession, historically and generally, is that all it requires is that you can get the job done. And if you come in with a passion for science, and background for that and you can tell a story, and do it on a deadline, then there will be a place for you. But if what you're saying is, will a glistening degree, in and of itself from a reputable institution of higher learning in a scientific field, make them say, 'Wow. You're our boy.' Not in and of itself, but it can in combination with other skills that you or your colleagues may possess; would make for a real killer combination that is welcome in many places in the profession. The degree itself, no, but if you can do the job and come with passion, absolutely, I'd say.

Q: I'm not necessarily looking for advice on how to get a journalism job, but I'm just saying that there is an opportunity out there for educated scientists to become journalists and maybe that should be looked at on a nationwide level, perhaps, more than it is.

Brown: Couldn't do any worse than we're already doing.

Q: How do you decide where to set the bar in terms of being an educator as well as a reporter? In other words, how do you determine who you are talking to when you write a piece, and do you consciously make them learn something, work a little bit to understand the piece, rather than just have it fed to them in the sense of learning science?

Brown: Ross, what are the assumptions that the Seattle Times brings to its table?

Anderson: I think that varies widely from one reporter to the next. [End of recording.]

PUGET SOUND RESEARCH '98

SESSION 4A

THE MANAGEMENT OF NEARSHORE HABITATS

Session Chair:

Megan Dethier
University of Washington

Functional Assessment of Created, Restored, and Replaced Fish Habitat in the Fraser River Estuary

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Introduction

The Fraser River estuary is probably the most intensively managed estuarine ecosystem on the Pacific coast of Canada because of the importance of the fish populations in the lower river and the intensive human use of the region. For example, the Fraser River supports the largest wild chinook population of any single river system in the world. The particular population, in the Harrison River, is of the life history type which shows an adaptation to estuarine rearing (Levings 1998). Because of the burgeoning human population of Greater Vancouver (population currently about 1.5 million people located primarily within the estuary) and the concentrations of marine industry such as deep-sea ports, it is a challenge to achieve sustainability.

In this paper I provide an overview assessment of bioengineering projects for restoration and compensation at the estuary. For comparison, I have commented on natural processes that lead to development of the various habitats. Over the past decade or so, fish habitat managers have developed techniques to try and achieve "no net loss of productive capacity of fish habitat" as specified under Fisheries and Ocean Canada's policy. Fish habitat mitigation[i], compensation[ii], and restoration are the key strategies to achieve this goal. Procedures have included vegetation transplants, channelization, artificial reef construction, and other techniques. Levings and Nishimura (1997) described the Fraser River estuary and summarized a detailed functional assessment of brackish marsh restoration projects in the estuary. In this paper, I provide comments on the other seven primary habitats.

Types of Habitat

For the purposes of this paper, I recognize eight (8) primary fish habitats in the estuary: brackish marshes, eelgrass, sand flats, mud flats, riparian vegetation, side channels, wet meadows, and salt marshes. Because of the differences in fish habitat classification methods (see Thom and Levings 1994) that have been used in the Fraser estuary it is difficult to provide both qualitative and quantitative estimates of fish habitat loss since European settlement. Exclusive of Sturgeon and Roberts Bank and Boundary Bay (total area of about 244 km^2), it is estimated that there were about 1032 km^2 of vegetated habitat (Levings 1998) in the estuary in the late 1890s, but the historical extent of unvegetated areas such as sand and mudflats has not been estimated. Most authorities agree (summarized in Kistritz et al. 1996) that between 70-90% of the wetland habitat has been lost since the late 1800s. Estimates of increase in habitat by bioengineering and natural processes are scarce. Kistritz (1996) calculated a net gain, primarily through restoration, of brackish marsh of about six ha in past decade or so, with an accompanying loss of sand and mudflat habitat that was planted with sedges (primarily *Carex lyngbyei*). This gain was achieved over the past 15 years or so during a period of industrial activity, and likely indicates an improvement in the management of the estuary. Hutchinson et al. (1989) suggested that brackish and freshwater marsh in the estuary and lower river had expanded substantially in the past century. There has been no systematic investigation of these expansions, but they likely occurred at a few locations several decades ago, possibly in response to training wall construction as explained below.

Procedures for Habitat Restoration: Successes and Problems

Over decades or centuries, natural succession of vascular plant communities in estuaries and large rivers occurs as shallow water fills in with sediment, allowing the development of marshes, then

wet meadows, riparian vegetation and finally wetland forests (Teversham and Slaymaker 1976). I have arranged my description of the various habitats to conform with this scheme.

Sand and Mudflats

Bioengineering

Because of the relatively low ecological value traditionally assigned to shallow water, unvegetated habitat in the estuary (e.g., Williams and Colquhoun 1987) there has been no attempt at creating sand and mudflats in the region. Many hectares of unvegetated habitat has likely been created by disposal of dredged sand (Envirocon 1980) but this has not been documented. In general, compensation for loss of shallow-water, unvegetated habitat has been difficult because of unavailability of terrestrial or filled habitat which could be lowered to proper elevation for fish use.

Because of the difficulty in creating shallow water sand and mudflat habitat in the estuary, there have been some "like for unlike" habitat switches in some parts of the estuary. Artificial reefs were first developed in 1983, at the Roberts Bank coal-loading terminal, by placing concrete pipe and pilings on the sea floor. The artificial reef was created to provide compensatory habitat for losses of habitat, including shallow-water sand and mud-flat habitat, that occurred through construction. The results were recently examined as part of a functional assessment of several bioengineering projects on Roberts Bank. An ecological survey conducted in 1997 (Subsea 1997) found that the hard substrates had been colonized by red algae, tunicates, hydroids, and wide variety of other epifauna and epiflora. However, the pipes and pilings appeared to be sinking into the substrate, and the -term future of the structures may be uncertain. The reefs also attract predatory fishes such as rockfish, which may feed on juvenile salmonids.

Natural Processes

Sand and mud-flat habitats are developed by bedload and washload sediments arriving into the estuary from upstream erosion. Wave and current energy and other hydraulic processes will tend to move sediments to an equilibrium slope. For example, on the foreshore of Sturgeon Bank, exposed to the Strait of Georgia, sand and mud flats show approximately a 1:20 gradient. As mentioned above, these habitats are usually rated as low value estuarine habitat based on their lack of vascular plant communities, but their function has never been adequately assessed. We do know that chinook salmon juveniles use sand flats on Sturgeon Bank and concentrate in the low-tide refuges for rearing (Levings 1980). It is likely that sand and mud flats are important building blocks for brackish marsh and other key habitats, and therefore any impairment in their development (e.g., blockage or removal of sediment from upstream sources) should be avoided.

Brackish Marsh

Bioengineering

Studies conducted under the DFO Fraser River Action Plan (1990–1993) have investigated the relative successes of brackish marsh transplants (especially sedge, *C. lyngbyei*) in the Fraser River estuary. They have shown that if elevations and sediment conditions are satisfactory, the plants will survive, and they are quite quickly colonized by invertebrates used as fish food (Levings and Nishimura 1996). However in a number of instances the transplanted marshes were found to be higher in the intertidal zone than natural marshes, and thus were relatively less accessible to fish. More recently, we conducted a study at the estuary in September 1996 at 13 transplanted and six natural sedge marshes to investigate the below-ground rhizome biomass as an index of restoration success. Results showed that the mean below ground biomass (excluding the top five cm of fresh material and previous years' leaves and stems) for transplanted marshes was not statistically significant ($p>0.05$). These results suggest that the transplanted marshes, which ranged in age from five to eight years, had developed rhizome biomass similar to natural marshes.

The above studies only examined a small subset of the marsh restoration projects, and there are numerous transplant projects that have not been assessed because no formal follow-up procedures were required. As well, except for very basic botanical measurements (e.g., plant survival), ecological performance criteria are not used.

Another class of restoration projects for brackish marsh, which has conducted by numerous citizens' groups, has involved removal of log debris from marshes. Anecdotal evidence suggests that the plants increase their productivity when debris is removed. However, there has been no published follow-up work to document these benefits.

Brackish marsh restoration or creation has been a common practice in the estuary, resulting in habitat switches in several locations, as documented by Kistritz (1994) and Adams and Williams (1998). In most instances sand or mud flat habitat has been raised or otherwise modified to allow sedges to be transplanted at the proper elevations.

Natural Processes

Because the Fraser River carries a very large bedload of sand as well as washload of mud, shoal areas are built up quickly which can then lead to colonization by brackish marsh. Thus an unquantified area of marsh has developed by natural processes (Hutchinson et al. 1989). Breakwaters and causeways have stopped this type of accretion in several areas of the delta, particularly near Iona Island where wave energy is focused. (Pomeroy et al. 1981). In other areas (e.g., Duck-Barber-Woodward Island in the inner estuary), construction of training walls has created backwater areas where sedimentation has led to development of marsh islands. On the foreshore of Lulu Island it appears the sediment from the washload is sufficient to allow seaward expansion of the foreshore marshes (e.g., seaward side of Lulu Island) (Hutchinson et al. 1989).

Sand islands were created in past decades from clean sand dredged for channel maintenance in numerous locations in the estuary. These locations have been successfully colonized by sedge marshes (e.g., Wiley, 1984), although this phenomenon has not been systematically assessed.

Eelgrass

Bioengineering

There has been one eelgrass (*Zostera marina*) transplant conducted in the Fraser River estuary. In November 1991, 96000 sprigs were transplanted into an area near the Tsawwassen Ferry Terminal, as part of a project to compensate for habitat lost owing to construction of a parking lot. Kistritz and Gollner (1995) conducted an evaluation of part of the transplant site in March 1995. Shoot density at the transplant site was 127 shoots/m^2 (s.e. 8.6) compared to 75 shoots/m^2 (s.e. 3.6) for a nearby reference site. Because of problems in identifying the boundaries of the original transplant areas, it was difficult to determine if the shoot density found was representative of survival for the 1991 plantings.

Natural Processes

Several detailed studies have examined the spread of native eelgrass (*Zostera marina*) on Roberts Bank, particularly in the intercauseway area. Harrison (1987) concluded that expansion of these eelgrass beds was enhanced by the deflection of turbid water from the Fraser River by the coal port causeway. Spread of the eelgrass was by encroachment of the rhizomes to sandflat habitat. An introduced eelgrass (*Z. japonica*) has also spread onto Roberts and Sturgeon Bank, likely by seeds. Expansion of this species onto Sturgeon Bank may have been enhanced by recent improvements in water quality because of diversion of sewage from the intertidal zone (Nishimura et al. 1996).

Salt Marsh

Bioengineering

An unsuccessful attempt was made to transplant cores of pickleweed (*Salicornia virginica*) into the Iona Island foreshore. Failure was likely due to sediment instability and salinity conditions (Pomeroy et al. 1981). However a related species has been cultivated elsewhere (Kamps 1962) and it is possible that salt marsh could be restored at the Fraser River estuary under the correct conditions.

Debris removal programs in salt marsh habitat have occurred, especially in Boundary Bay. However, there has not been any documentation of the benefits.

Natural Processes

Salt marsh plants are not adapted to the brackish conditions near the river mouth where sand and mud are deposited. Salt marshes are dependent on marine processes such as longshore drift for sediment supply and expansion. For example, before construction of the BC Ferry Terminal causeway, the Tsawwassen salt marsh was relying on eastward movement of sand from Point Roberts Bluff. Saltmarsh vegetation (*Salicornia virginica, Distichlis spicata*) successfully colonized a dredge-spoil island on Sturgeon Bank, near Steveston, resulting in the development of 0.5 ha of habitat within about 10 years (Levings 1998).

Wet Meadows

Bioengineering

There has been no attempt, as far as is known, to restore this kind of habitat. However because certain brackish marsh restoration projects have been built too high in the intertidal zone, they are dominated by wet meadow species (e.g., rushes such as *Juncus effusus* (Levings and Nishimura 1996). This habitat was once one of the most extensive vegetation units in the Fraser River estuary (Kistritz et al. 1996). However because the habitat occupies the highest elevation of the intertidal zone, and in some instances, is actually on the flood plain, wet meadows were the first areas to be diked and converted to farmland. The importance of wet meadows as fish habitat is poorly documented, but these vegetation communities, as well as wetland forests, supplied significant amounts of carbon to the estuary ecosystem before they were converted to agricultural areas (Healey and Richardson 1996).

Natural Processes

Wet meadows develop on accreted sediment at higher elevations in areas that are infrequently flooded. In the botanical succession process, they follow brackish marshes but precede riparian vegetation. Eventually these habitats likely become floodplain forests, which are important for maintaining the integrity of the delta by reducing erosion.

Riparian Vegetation

Bioengineering

Riparian vegetation is planted on relatively steep shorelines where the plants can stabilize sediment as well as provide detritus and insect production. There have several kilometers of shoreline in the Fraser River estuary that have been transplanted with riparian vegetation such as willows (*Salix* spp.) and red ochre dogwood (*Cornus stolonifera*) (DFO, unpublished). The plants characterizing this particular habitat are said to show high survival after transplanting (Adams and Whyte 1990) but there are no published assessments available in the Fraser River estuary.

Natural Processes

Because riparian plants do not tolerate regular flooding, they do not necessarily colonize the

intertidal zone. Riparian vegetation establishes on the river shorelines that have been built up by the process of sedimentation, especially following major freshets when the elevation of sand bars and banks are raised. Riparian vegetation has also colonized several dredged sand islands in the Fraser River estuary (Envirocon 1980).

Side Channels

Bioengineering

In efforts to recover shallow water habitat, there have been a number of projects in the Fraser estuary where ditches or channels were cut into terrestrial or irregularly flooded land. For example, at Iona Island, about 400 m of ditch was dug into a grassy field, enabling high-tide flood waters to penetrate the field. Preliminary analyses showed that aquatic invertebrates colonized the constructed channel (Levings and Nishimura 1996). In another project, a channel about two km long was dug through a cottonwood stand, then connected to a culvert bringing water into the site from the North Arm of the Fraser River at Burnaby Bend. In this instance, riparian vegetation and brackish marsh was planted along the channel edge to help stabilize the sides of the channel (DFO, unpublished data).

Natural Processes

The processes leading to natural development of side channels in the Fraser estuary is dependent on the particular habitat being considered. For example side channels through sand flats are usually created by erosion due to river currents, whereas those through mud flats develop as water drains off following high tides (e.g., Luternauer 1980). Channels through salt marshes develop by tidal drainage as well, but in this instance the banks of the channels are stabilized by plants, as observed at the Tsawwassen salt marsh on Roberts Bank (Hillaby and Barrett 1976).

Summary : What Ecological Processes Does This Habitat-By-Habitat Approach Ignore?

After about a decade of restoration activities in the Fraser River estuary, applied ecologists have accumulated valuable experience with applying bioengineering techniques to restore or replace lost habitat. However, few data sets exist for for assessing the "value" of particular projects. This brief assessment suggests all the bioengineering restoration and compensation techniques reviewed have had varying degrees of success—or at least enough success that their proponents continue to seek, and obtain, funding for their work. Unfortunately, even though habitat conversion, creation and replacement is widespread in the Fraser River estuary, little consideration has been given to the landscape level consequences of the many individual restoration projects that have been undertaken. Therefore, before future bioengineering projects are implemented, there are several important ecological and policy considerations that need to be taken into account to place restoration efforts in the context of estuary management plans. Some of these recommendations are summarized below.

1. Implement Landscape -Level Planning

Bioengineering projects to date have been considered on a project by project basis without explicit consideration of landscape level objectives. As the examples have illustrated, bioengineering projects are not necessarily reflective of the spatial patterns of the eight primary habitats at the landscape level. The science of landscape ecology should be applied to estuarine habitats when planning restoration in specific reaches of the estuary. As explained, the sediments, plants, and water levels interact both in time and space to create the landscape units, or mosaics of habitats, that we see at any point in time. The Oceans Act (1997) emphasizes ecosystem management, and the rapidly developing science of ecological geography (e.g., Bailey 1996) shows that habitats cannot be managed in isolation from each other. Therefore, we recommend that existing GIS inventories (such as those maintained by the Fraser River Estuary

Management Program) be upgraded and used to compare the proportional representation of the various habitat types at various spatial scales in the Fraser River estuary currently to historical patterns. This will facilitate an objective appraisal of which habitat types have been lost or gained and in what areas. At a minimum, this information can be used in the future to give higher priority to those bioengineering projects expected to restore or recreate those habitat types that have sustained the greatest loss in the past rather than on an ad hoc project-by-project basis.

2. Ecosystem Research and Monitoring

After about two decades of applied fish habitat research in the Fraser River estuary and others in the northeast Pacific, there are still major uncertainties about the fish habitat value of specific habitat types. In addition, it is unclear what the benefits are of bioengineering one habitat type over another. For example what is the role of sand and mud flats in the estuarine ecosystem compared to brackish marsh habitat? Should we continue to tradeoff sand and mud flat habitats for brackish marsh? Although this situation cannot be rectified immediately, standard criteria should be developed for assessing habitat differences in the future. To be effective, these criteria need to be monitored regularly at restored and natural areas to determine whether restored areas are producing the expected results.

3. Ecological Succession

Natural processes such as sedimentation and colonization by various plant species convert one habitat type to another over time, but current habitat restoration does not take this phenomenon into account. The ecological succession of plant communities occurs on a scale of decades, and is usually punctuated by rapid erosion and accretion events such as those that occur during major freshets. Responsible plans for ecosystem and habitat management must take these changes into consideration, and a long-term perspective is required.

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Puget Sound Nearshore Habitat: A Summary of Current Threats and Obstacles

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Background

The loss of Puget Sound nearshore habitat[iii] concerns resource managers and scientists because these areas play a critical role in maintaining healthy populations of marine life. A marine science panel created through an international effort between Washington and British Columbia found that nearshore habitat is being lost at an alarming rate and stated that efforts must be taken immediately to improve protection of this important area.

The Puget Sound/Georgia Basin Task Force created the Nearshore Habitat Loss Work Group (composed of tribal, state and federal government representatives and two non-governmental organizations) in order to respond to this concern. The Work Group found that there was little information available regarding current activities causing the most harm. In order to make recommendations for improved protection of the nearshore, the Work Group needed to know what was causing the greatest damage, and how the regulatory system was dealing with the problems.

In 1993, Thurston County documented the prevalence and rate of shoreline armoring in Thurston County (Morrison, Kettman and Haug, 1993). Those data show a 110% increase in the amount of shoreline armored from 1977 to 1993. Budd Inlet, the most heavily developed marine water body in the county, had 47% of its shoreline armored in 1993. The Thurston County study demonstrated that armoring caused tremendous habitat alteration in Thurston County. It provided no information outside the county and no comparative data were available. Little information was available regarding current Sound-wide nearshore losses associated with human activities.

Some shoreline permit data are available through individual local governments but the databases are limited and often difficult to obtain. Data for Hydraulic Project Approvals are compiled by the Washington Department of Fish and Wildlife (WDFW) (data are reliable after 1990), but provide only number of permits issued without any information on size of impact or type of habitat altered.

This study was conducted for the Work Group members to better understand what human activities are causing damage to nearshore habitat and how the regulatory system is addressing the most damaging activities. We interviewed 28 people with a variety of knowledge and experience to find out what they were witnessing out on the nearshore and what activities they were concerned about. The people interviewed included county, city and tribal shoreline managers, federal and state regulators, scientists, a former Shoreline Hearings Board member and a former county commissioner.

Findings

The findings of this study include an analysis of the current regulatory system and a list of other needs pertinent to the management of the nearshore. None of the findings are terribly surprising. Many of the issues have been raised in previous studies, but have not been acted on.

The greatest threats to the nearshore according to those interviewed are shoreline armoring, residential development, large commercial or industrial development projects, water quality and overwater structures (e.g., docks, piers). *Spartina* infestations also appear to be a growing problem.

The management of the Puget Sound nearshore is full of gaps. The regulatory system is piecemeal and inadequate. There are many agencies and different levels of government involved in regulating the nearshore, but no one entity is responsible to manage or evaluate the system holistically. The number of agencies involved in the regulatory business gives the public the perception that the area is heavily regulated.

There is an important difference between the way in which commercial activities and single-family residential activities are regulated. Single-family residential development activities are generally given much less rigorous review and considered to have insignificant impacts. Sound-wide, however, these individual activities add up to a significant amount of nearshore habitat losses that are not being tracked, tallied or evaluated. Individual residential losses are also generally not compensated for through mitigation. Commercial or industrial activities receive tremendous scrutiny and undergo mitigation sequencing (a policy that requires applicants to avoid, minimize, rectify and compensate impacts in that order of preference).

An important attribute of the regulatory system is that local governments have a great deal of authority to limit, condition or deny development projects that would cause harm to the nearshore. Local governments also have the ability to customize regulations to the specific needs and sensitivities of their shoreline through their shoreline master programs. Several powerful limitations are present at the local level however, and they include: the political will to use regulatory authorities; knowledge of the biological resources that use the nearshore; and understanding the effects of different types of development to the nearshore. Political will can be a tremendous obstacle.

Another shortcoming of the current system is that there are inadequate inventories of nearshore habitats and biological resources. Maps are outdated and inaccurate. Without better resource information, regulators can not make a case for preventing damage to the resources. For example, inventory of surf smelt spawning areas are very limited, yet this species can be greatly affected by armoring. WDFW officials can not deny or condition a permit application unless the site has documented surf smelt populations, even if the site appears to be optimal for their spawning.

Most of the Puget Sound local shoreline master programs were written 15–20 years ago and have not been significantly updated to reflect growing development pressures and cumulative impacts of development activities. Nor do they recognize the impacts that occur with each individual permit application. This is true for state and federal regulations as well.

State and federal agencies are limited in their authorities provided through the Shoreline Management Act, the Hydraulics Code, and the Clean Water Act, and can only intervene in specific circumstances. The Department of Ecology's role in reviewing local substantial development permits is an important mechanism to help prevent damaging development activities. WDFW field staff provide very important technical assistance to local governments in the processing of hydraulic permits. In both cases, there are significant limitations in the agencies' authorities that stem from local government's abilities to exempt single-family residential bulkhead and dock projects as directed in the Shoreline Management Act. Federal agencies rarely are involved in residential permits.

Because of the flexibility allowed in developing local shoreline regulations, the nearshore is being regulated differently throughout Puget Sound. There are 12 counties, 34 cities, seven tribal reservations, and numerous state-owned and federally owned lands. Each jurisdiction and agency has its own method for regulating their piece of shoreline. In many cases, the individual jurisdictions and staff are focused on upland considerations rather than preventing damage to habitat at or below the shoreline. The result is a variety of permitting systems with varying degrees of protection to the nearshore. A few jurisdictions recently made changes to their shoreline management programs aimed to better protect residences from erosion problems and at the same time improve habitat protection. Some jurisdictions now process bulkhead requests as substantial development permits and require geotechnical justification.

The majority of local governments, however, do not process single-family residential bulkhead requests as substantial developments. This means that there may be no evaluation of whether or not the bulkhead is needed to control an erosion problem. Most of those interviewed said that many shoreline landowners automatically assume that a bulkhead is needed to prevent erosion. In some cases landowners want a bulkhead for landscaping purposes or feel that it is necessary to maintain real estate values.

Shoreline construction activities have significant effects to the nearshore because the vegetation is cleared and replaced with impervious surfaces. Roofs, driveways and lawns create impervious or nearly impervious surfaces that cause rainwater to drain down bluffs (rather than percolating into the soil) and

create additional erosion problems. The addition of lawn watering and on-site septic systems further exacerbates saturation problems at the top of bluffs. Some landowners incorrectly believe that a bulkhead at the toe of a bluff will minimize erosion at the top. More information is needed to clarify the utility of bulkheads and to enable landowners to prevent erosion caused by excess drainage.

When the guidelines for shoreline master programs were originally written in the early 1970s, there was little concern over the construction of bulkheads or docks for single-family residences. The language in the Shoreline Management Act was written to facilitate the construction of these "normal features" for waterfront homes. Currently, however, we understand that bulkheading and other types of armoring can cause beach scouring and destroy natural habitat for many types of baitfish. The damage associated with armoring is known and documented (Thom, Shreffler, and Macdonald, 1994), but there is no comprehensive tracking of armoring rates Sound-wide. We also know that over-water structures such as docks and piers can cause shading problems for eelgrass. Despite this knowledge and documentation in the literature, regulations have not been updated to limit the construction of these features.

Physical alterations of the shoreline are not the only activities causing problems. Scientists are increasingly concerned about the effects of runoff to nearshore habitats. Eutrophication at the mouth of Chimacum Creek in Jefferson County and in other areas of Puget Sound have been found (Thom, 1997). Storm water runoff, farm runoff, and failing on-site septic systems all contribute contaminants to the nearshore and ultimately to the Sound. Few local governments have a handle on preventing these problems.

All of the activities causing damage to the nearshore can be minimized or prevented through updated regulations and better education regarding the impacts of the activities. Unfortunately, education programs remain underfunded.

Permit tracking is extremely limited but improvements could help to document cumulative effects. The Washington Department of Natural Resources (DNR) has prepared an analysis of shoreline modification throughout Puget Sound (Figure 1). Berry (1997) found that approximately one-third of Puget Sound's intertidal zone, the area that is regularly covered by water, has been modified. That data along with information from interviews demonstrate that there are regional differences in the amount of nearshore that has been lost or altered and there are different causes for those losses.

Key Points

- Nearshore habitat continues to be lost incrementally and insidiously due to both direct physical alteration and water quality degradation. Major activities of concern are bulkheads, development and nutrient runoff. Single-family residential development activities, such as bulkheading and dock construction, generally do not require compensatory mitigation and cause continued loss of nearshore habitat. Large development activities are required to provide compensatory mitigation, but the mitigation projects do not always achieve success.
- Local governments are empowered to protect the nearshore by minimizing development impacts, but local government staff and leaders often do not understand the value and functions of the nearshore or the connection between upland/shoreline development and degradation to the nearshore.
- The piecemeal approach to managing the nearshore will not enable us to evaluate the health of the nearshore holistically. Permit-by-permit processing does not allow an agency to evaluate cumulative effects. Several development activities shown to be harmful to the nearshore are considered "insignificant" to the environment by state and federal laws.
- Regulations, particularly shoreline master programs, need to be updated to reflect current knowledge about the effects of development activities (e.g., bulkheading, runoff) and to better protect our marine resources that rely upon a healthy nearshore (e.g., salmon, surf smelt).

There is a great need for better education and dissemination of research regarding the nearshore. Key audiences are local government staff, shoreline landowners, developers and elected officials. The full report Puget Sound Nearshore Habitat Regulatory Perspective: A Review of Issues and Obstacles is available from the Puget Sound Water Quality Action Team.

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Site Selection for Estuarine Habitat Restoration: Model Criteria

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The Importance of the Estuary

Puget Sound rivers have broad flood plains that historically have contained relatively large areas of tidally influenced salt marsh and mud flat. In the past 150 years, we have destroyed over 70% of these salt marsh and mudflat habitats through diking, draining, and filling (White, 1997). Wild salmonid stocks are depressed throughout Puget Sound, and habitat loss, along with overharvest and hatchery practices, has been indicated as a primary factor in their decline. Chinook fingerling stop in the salt marshes and mud flats for weeks, and even months, to feed and gain strength for their ocean journey (Hayman et al., 1996). Because fish spawned over an entire river basin must pass through the estuary to enter the marine environment, healthy estuarine habitats are critical to salmon survival and production.

The Snohomish, Stillaguamish, and Skagit Rivers have no dams in the lower reaches that block salmon passage (like the Green and the Cedar), have not been moved from their native channels (like the Cedar and the White), and are lightly impacted by industrial development relative to the Duwamish and the Puyallup. These rivers, along with the Nisqually, the Nooksack, and the Elwha, represent the best opportunities we have to restore wild chinook runs in Puget Sound.

With this in mind, People for Puget Sound formed a partnership with the U.S. Fish and Wildlife Service Puget Sound Program and the Pacific Coast Joint Venture to model site selection for estuarine restoration in the Snohomish Delta. This paper explains the methods by which the project team selected and rates sites for our Snohomish Estuary Restoration Blueprint.

Estuary Habitat Restoration

The restoration of saltmarsh and mudflat habitat in Puget Sound is a very new science. Most of this kind of restoration has been accomplished in the 1990s on sites selected largely because of their availability. As readily available project sites have become scarcer, the need has grown for a way to assess the estuary from the point of view of resource needs. We set out to create a set of criteria by which entire river deltas could be screened to identify and prioritize potential intertidal restoration project sites based largely on ecological principles.

The starting point for developing our criteria was "Restoration of Urban Estuaries: New Approaches for Site Location and Design" by Schreffler and Thom (1993). While this report provided us excellent guidance, it did not reveal the site selection tool we were looking for. Our goal was to create a set of selection criteria that could be completed through field observation, interviews, and map and document research. We hope that we have developed a scientific tool that watershed groups can use without spending the time and money necessary for stringent scientific study.

We purposefully limited the consideration of social and political factors in our site selection protocol. We do believe they are real factors, but we believe that it is best to begin from a scientific base and then take advantage of the knowledge in the local community to further refine the rating of sites.

Developing the Criteria

We began by defining our project area as the extent of historic tidal influence in the Snohomish watershed. Snohomish County allowed us to use Geographical Information System (GIS) coverages produced through the 1995 Snohomish Estuary Wetland Integration Plan (SEWIP). We divided this geographical coverage into potential restoration sites that suggested themselves based on the meandering of sloughs and the placement of dikes. For the remaining sites, we developed our criteria based on basic ecological principles such as the role of habitat corridors and the relationship between site size and species diversity. The criteria award a maximum of four points for major considerations, fewer points for lesser considerations, and negative points for negative conditions. The criteria are detailed as follows:

1) Critical Habitat (0 to 4 points)

For the Snohomish estuary, we define the target habitat corridor as those sites adjacent to Ebey and/or Steamboat Sloughs.

- Within the target habitat corridor (2)
- Adjacent to current stem, channel, or slough (1)
- Adjacent to historic stem, channel, or slough (1)
- Entirely outside corridor with channels (0)

Discussion

For the estuary, the stems, channels, and sloughs are the primary corridor of travel for fish and wildlife. Since the Snohomish has high potential for wild chinook recovery, we decided to weigh our criteria in favor of salmon. (Coho also rely heavily on the estuary, and NMFS has announced their intentions to propose a coho listing.) In order to concentrate our efforts along one corridor, we awarded two points to sites directly adjacent the "target habitat corridor." For the Snohomish, it was logical to chose Ebey and Steamboat Sloughs as the habitat corridor, because it has the greatest amount of natural habitat in the lower Snohomish system.

It can be argued that we should have given higher priority to main-stem projects, since very little habitat exists there and it takes the highest river flow. However, salmon seek out side-channel habitat, and developing a continuous corridor would give salmon choosing that route a much higher likelihood of survival, as opposed to spreading risks and benefits out over the whole lower river system.

Since we are convinced that dike-breaching projects offer some of the highest benefit, we awarded one point to sites adjacent to a current stem, channel, or slough. We also awarded one point to sites adjacent to historic sloughs, in recognition of the potential for re-creating off-channel habitat in a place where it once existed.

2) Chinook Habitat Zones (0 to 2 points)

High-value chinook rearing habitat.

- Lower intertidal (2)
- Middle intertidal (0)
- Upper intertidal (2)

Discussion

An eight-year study, carried out in the Skagit estuary by the Skagit System Cooperative and nearly complete, shows that ocean-type juvenile chinook stop to feed there for extended periods (several weeks)—first in the upper portion of the estuary, and then in the lower. We divided the estuary into three equal portions and awarded two points to sites in the first or third portions. The divisions included

mud flats at the lower end and non-saline waters at the top of tidal influence.

This criteria should be adjusted and refined as other salmon become listed (coho may rely heavily on the middle portion of the estuary) and as more research becomes available.

3) Percent Habitat Increase (0.2 to 4.0 points)

The potential increase in the total area of existing estuary habitat.

0–5%	(0.2)	21–25%	(1.0)	41–45%	(1.8)	61–65%	(2.6)	81–85%	(3.4)
6–10%	(0.4)	26–30%	(1.2)	46–50%	(2.0)	66–70%	(2.8)	86–90%	(3.6)
11–15%	(0.6)	31–35%	(1.4)	51–55%	(2.2)	71–75%	(3.0)	91–95%	(3.8)
16–20%	(0.8)	36–40%	(1.6)	56–60%	(2.4)	76–80%	(3.2)	96–100%	(4.0)

Discussion

This criteria is intended to equalize the relative value of sites from estuary to estuary by comparing the area of the site to the area of habitat already conserved and restored in the estuary. For instance, a two-acre site would score well in the Duwamish, but poorly in the Snohomish. For the Snohomish we calculated the existing estuary habitat at 1453 acres. For those target sites where the goal was not full restoration (such as dike setbacks on private land), we calculated their potential habitat area as the length of the site along a migration corridor (eg. slough) multiplied by a 150-foot restored buffer on the site. Our scale for rating this criteria is linear, with 0.2 points awarded for every 5% increase in habitat.

4) Site Area (0.33 to 4.0 points)

Habitat benefit based on area (in acres).

0–0.25	(0.33)	2.1–4.0	(1.66)	32.1–64.0	(3.0)
0.26–0.5	(0.66)	4.1–8.0	(2.0)	64.1–128.0	(3.33)
0.6–1.0	(1.0)	8.1–16.0	(2.33)	128.1–256.0	(3.66)
1.1–2.0	(1.33)	16.1–32.0	(2.66)	>256.1	(4.0)

Discussion

This area rating recognizes the fact that species diversity increases as the site area increases. With estuarine restoration, larger sites are more likely to provide elevations amenable to highly productive plants such as *Carex lyngbyei*, they are better able to bear outside pressures such as pollution invasive species, and they are more likely to be self-buffering against disturbances such as noise of lights. Larger sites can also present an efficiency of scale that can keep down the per-acre cost of restoration.

Since the relationship between size and benefit is nonlinear, we developed a scale base on the function $y = -36.392 + 19.596 \log x$ from Shreffler and Thom (1993) where y equals the number of wetland plant species and x is site area in square meters. Shreffler and Thom's analysis is only empirically valid for values of $x<500\ m^2$. We have extended use of this equation beyond the empirical data because it yields an accelerated decrease in benefit for species numbers with increasing site area, a result that is intuitively and practically appealing. Because the validity of the function has not been determined for larger sites, we define y here to be the "size index" rather than species number.

Since doubling the area yields a linear increase in species number, we developed the index for sites ranging in size from a small urban restoration project (<0.25 acres) to larger rural projects (>250 acres). We assigned all sites above 256 acres the same value because Shreffler and Thom indicate that the size threshold for completely self-sustaining estuarine wetland is between 200 and 300 acres.

This method requires 12 geometric size steps to cover three orders of magnitude in site size. To convert the size index to a 0- to 4-point scale for evaluating potential restoration sites, we assigned each size step incremental values of 0.33.

The results of this analysis are shown below:

Site Area (acres)	Size Index	Scaled Value
>0–0.25	23.9	0.33
>0.25–0.5	29.8	0.66
>0.5–1.0	35.7	1
>1–2	41.6	1.33
>2–4	47.5	1.66
>4–8	53.4	2
>8–16	59.3	2.33
>16–32	65.2	2.66
>32–64	71.1	3
>64–128	77	3.33
>128–256	82.9	3.66
>256	88.8	4

5) Plant Community (0 to 3 points)

Presence is defined as 25% or greater coverage of the site.

- Non-native (Yes=1)
- Invasive (Yes=2)

Discussion

Since native animals are adapted to survive using native plants, this criterion awards points for the presence of non-native plants, based on the argument that manipulation of plant communities is often the most cost-effective type of restoration. One point is awarded when a site contains 25% or greater coverage of non-native plants such as pasture grass or crop plants. Two points are awarded for invasive species because they threaten the rest of the site and/or other sites and should be handled with more urgency.

6) Buffer (0 to 4 points)

Percentage of perimeter covered by at least a 100-foot depth of native vegetation or waterway.

0%	(0)
1–25%	(1)
26–50%	(2)
51–75%	(3)
76–100%	(4)

Discussion

Vegetated buffers are important because they can "trap excess sediments and purify water entering the aquatic system and function as a barrier to disturbance by noise, movement, etc." (Shreffler and Thom, 1993, p. 53), and provide shade, cover and insects for juvenile fish. We have taken the minimum depth suggested by Shreffler and Thom (100 feet). For the highly impacted estuaries of Puget Sound, a

100-foot buffer anywhere along the perimeter of a restoration site would seem a luxury.

7) Restoration Ease (-2 to 0 points)

Not diked (0)

Diked, not filled (-1)

Diked and filled (-2)

Discussion

This criterion is designed to give weight to more cost-effective projects. A site under tidal influence with the presence of invasive species is likely to be cheaper to restore than a site that is diked and filled. It could be argued that invasive species are sometimes more costly per acre to remove or control. But in a case such as Port Susan, where *Spartina* exists and could spread to cover the entire perimeter of the bay and eventually spread around the Sound, the benefits cover the immediate area and beyond.

8) Impervious Surface (-4 to 0 points)

The percentage of the site that is impervious due to human action.

0%	(0)
1–25%	(-1)
26–50%	(-2)
51–75%	(-3)
76–100%	(-4)

Discussion

This criterion has the effect of further factoring the ease of restoration, since developed sites are more expensive to restore and have a higher chance of being contaminated. But this criteria is designed to take into account the fact that rating systems such as this one cannot assure that the best sites will actually be restored first. Impervious surface signals human habitation and/or business activity, and with this comes the chance that restoration proposals will meet with resistance. We hope that it will become more popular for landowners to restore portions of their land to habitat. But where unoccupied and developed sites exist, they should receive some priority.

Totals

For the Snohomish, we totaled the points and split them into three equal sections measured from the lowest score to the highest. We decided not to rate on a curve because we wanted a more "pure"" score that we could further adjust based on political and social factors known about particular sites—such as efforts already under way. The data are reported in Table 1 and the resulting GIS map in Figure 1.

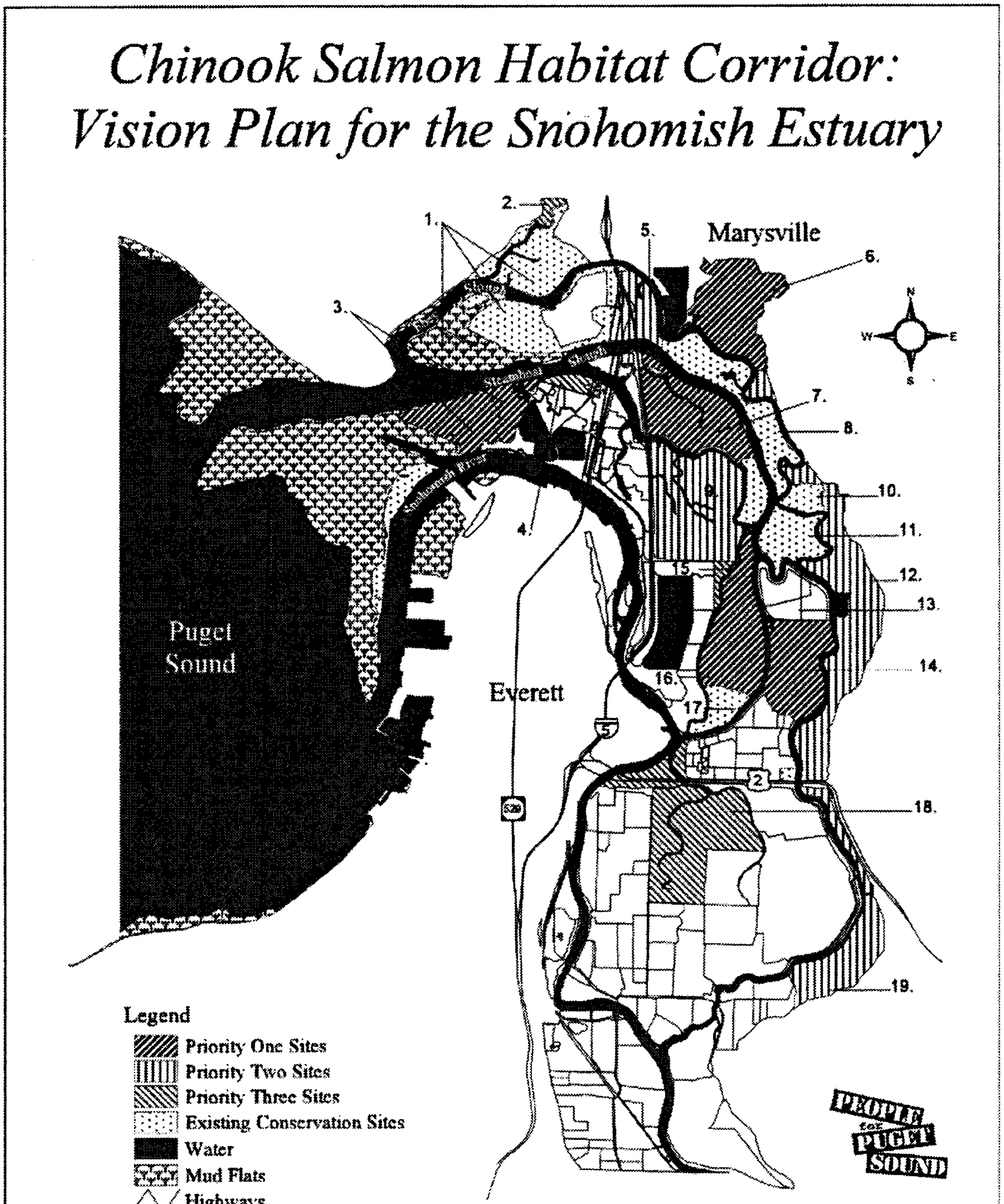

Figure 1. Chinook salmon habitat corridor: visitation plan for the Snohomish estuary.

Table 1. All sites considered in the study along with site scores developed from criteria and restoration priority resulting from the scores. Range for: priority 1 = 11.64–14.02, priority 2 = 9.25–11.63, priority 3 = 6.86–9.24. Sites already conserved and restored sites did not receive a score.

Site Number	Site Name	Site Score	Priority
2.	North Quilceda Creek	6.86	3
3.	Smith Island mud flat & salt marsh	11.8	1
4.	Smith Island Sliver	9.20	3
5.	Hayes Property	10.73	2
6.	Queloot	12.00	1
7.	Biringer Farm	14.00	1
8.	Mid Ebey Island		
9.	North Smith Island	11.40	2
10.	Nyman Property		
11.	Otter Island		
12.	East Ebey Slough	9.53	2
13.	South Ebey Island-A		
14.	South Ebey Island-B	11.80	1
15.	Smith Island Sliver	8.86	3
16.	South Spencer Palustrine	14.00	1
17.	South Spencer Estuarine		
18.	Deadwater Slough	5.53	3
19.	Drainage District Six	10.26	2

Conclusion

We believe that this tool, while simple, has the advantage of being extremely cheap and fast. The costs could be lowered further by using ratings produced by skilled volunteers. We plan to further test this system on other rivers, with the hopes of rating estuarine restoration sites in 12 major rivers around Puget Sound in the next few years.

Acknowledgments

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An Integrated Adaptive Approach for Planning and Managing Coastal Ecosystem Restoration Projects

Ronald M. Thom
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Abstract

The ecological performance of ecosystem restoration projects is uncertain. For this reason, numerous major restoration programs are recommending the incorporation of adaptive management principles into the planning process for restoration projects. However, the way that these principles are to be applied to maximize the probability of success is generally not specified. The present study developed a method for applying the principles of adaptive management to planning and managing coastal ecosystem restoration projects. The method employs a conceptual model to couple restorative actions to performance goals. For management, the method uses a system-development matrix to assist in identifying the state of the system for which restorative actions are being applied. The matrix defines development in terms of structure and function, but can accommodate other performance and development characteristics. Monitoring of the system provides input on where the system fits within the matrix. Phrases in the matrix identify causes resulting in the state of the system and point toward possible corrective actions to be taken if needed. Successful tests of the matrix have been done on projects involving infaunal community development on dredged material, seagrass system restoration, and a tidal marsh system restoration.

Salt Marsh Re-Colonization

Keith Dublanica
Skokomish Indian Tribe

Abstract

The Skokomish Indian Reservation sits on lower Hood Canal, at the mouth of the Skokomish River, at the southeast corner of the Olympic Peninsula. The 5,000-acre reservation includes approximately 2,200 acres in a combination of estuarine and palustrine wetlands. Within the estuarine community, portions of the landscape were sold by tribal members, diked, then drained in the late 1930's for agriculture. These two areas, referred to as the east and west cells, cover 600 and 800 acres, respectively. The ground has laid fallow for most of the last decade. A seawall facing Hood Canal experienced a breach in December 1994 due to flooding from a rain-on-snow event, high tide and offshore winds.

The Skokomish Tribe has been tracking the changes in salt marsh re-colonization of the formerly diked areas, using aerial infrared photography, vegetation transects, and salinity and sediment measurements. Redox, biomass, and other attributes are intended for later quantification. The study area has a reference, undisturbed high marsh, treated as a control, as well as an intact diked area as a secondary control. The Black Hills Audubon Society has assisted in migratory bird counts on the newly exposed mud flats. Because the landscape is home to the Skokomish Indian Nation, there are elements of cultural as well as ecological restoration that come into play.

The Skokomish Tribe has been involved in re-securing the landscape back to tribal trust status, and is currently embroiled in the Federal Energy Regulatory Commission (FERC) re-licensing of Tacoma Public Utilities Cushman Project, #460. It is the tribe's desire to secure the landscape and to breach additional sites within the diked network identified by the Army Corps of Engineers as the most appropriate. Coincidentally, the breach of 1994 was a major area identified by the Corps in a report submitted earlier that month.

4A: The Management of Nearshore Habitats

Questions & Answers

Q: I worked on the Bainbridge Shoreline Plan, and when we did that, I know, I had a great deal of difficulty finding information about the impacts of docks, particularly on salmon. I heard allusions to that, but even in querying fisheries scientists I couldn't get much definitive information. This was a couple of years ago. Did you find, in your looking at that issue, that there actually are some studies that clearly document impacts of docks on migration of salmonids?

Broadhurst: There is very little and it is one of the issues that came up. People said that there seems to be more knowledge out there than is being put in the literature. And I think it's a matter of agency staff, particularly Department of Fish and Wildlife technical staff, who are out there and seeing a lot of things, it's really hard for them to get the time to put this stuff down on paper and document it. And I think there's a real crying need. There are a couple of references that I would be glad to show you and I could send you a copy of the final report.

Comment: Just for your information, this year the WSDOT is funding an effort to look at exactly that issue; over water structures and fish movement. And the first thing is going to be a workshop, I think it's on April Fool's Day, in fact, where people who know something or are interested in this, will get together and lay the data on the table and throw away the myth. Let's see what we really understand, and let's see what we need to find out. So it's going to happen this year.

Comment: Annette Olson at the University of Washington is one of the main people that I know of looking at over water structures.

Comment: The other comment I had, based on the Bainbridge Island experience, is that one of the biggest hindrances to making improvements, particularly in individual family housing building, is the grandfathering that gets factored in when you have very minimal setbacks of everybody else and you have one vacant lot there's a very strong political argument that they can also be 25 feet from the shoreline and that tends to be kind of a domino effect to keep everybody right up close to the shoreline.

Comment: My name is Bob Duffy. I just had a couple of observations. I think that the methods that you showed for minimizing impacts to the marine shoreline could also be translated, to a large extent, to upland areas, rivers and lakes, as well. So for folks that are involved in the development of regulations, that might be something to consider. And then my second observation is that I've been continually frustrated with the tracking of cumulative impacts which was one of the things that the SEPA regulations in the state of Washington have been designed to do. And I just feel like we should encourage jurisdictions that are issuing permits to take a little bit more responsibility for tracking cumulative impacts. I don't think that they have to take the full burden of doing that, but they need to start contributing somehow to maybe putting down the length of the dock in a database somewhere, or the length of a bulkhead somewhere. And eventually translating, through some policy or regulation, how they want to manage that information on the cumulative impacts.

Broadhurst: One thing that I heard from the locals, and this was up in San Juan County, I particularly remember, they really want to know how they can limit docks. The biggest tool they had was viewshed, and if it was interfering with somebody's view, then they had means of limiting that dock project. But they are crying out for more information on how to be trained or how to understand how to use regulations in a cumulative way. That seemed to be a huge need.

Comment/Question: My name is John Houghton with Pentec Environmental. I wanted to respond to the lady's comment back here. We actually did a study for the Port of Everett last spring on effects of finger piers on juvenile salmon migration. I'd be happy to share that with anybody, and also to participate in this DOT thing. One thing that comes to mind in looking at some of the pictures that Colin showed about the Fraser River Delta, and I've seen it elsewhere where people do these nice habitat creations along the shoreline of estuaries, and then they feel compelled to put logbooms to protect those areas from wood debris. I would maintain, based on our observations of juvenile salmon movement, that those same log booms will very effectively preclude salmon from using those areas if they are fully intact, the fish will just swim right along the logbooms as if that were the shoreline. Who is organizing this thing on the 1st?

A: Si Simenstad is organizing it.

Comment: One observation. I was thinking when Ron was giving his talk that he was analyzing the whole, you know, how do you do restoration, and I thought we should be looking at all of our shoreline that's already intact and making sure that those pieces of it are in place. Maybe that should be model for our management. We seem like we might be holding restoration sites to a much higher standard than we are the rest of the shoreline.

Comment: My name is Peter Bahls. I'm a habitat biologist for Port Gamble Tribe, so I get to review some of these permits and work with the state habitat biologists, and I'd just like to thank you for your talk. I think what you are talking about is one of the most ignored aspects right now of habitat protection. It's incredible to me that we still get all these bulkhead permits, all these dock permits coming through. And we know the cumulative effects, and supposedly we have SEPA to regulate this, and yet these permits routinely go through SEPA and there's no way to stop them. And one thing I just wanted to mention is you didn't mention DOE's recent, I think it was a two year report of the cumulative effects of bulkheading, and that hasn't seemed to trickle down in terms of a regulatory effect at all.

Broadhurst: I'm amazed at it too. I think a lot of waterfront owners think that it's, well, it's been considered their right to do a lot of development activities, and certainly that's the way the state Shoreline Management Act was written.

Q: I'm Doug Bulthuis. I work for the Padilla Bay Research Reserve. I think it was your last slide that emphasized the fact that there are so many different jurisdictions throughout Puget Sound. Implicit in what you said was that we'd be better off if there was one jurisdiction, or if we would regulate everything through one level, and I think it's a natural tendency I have too. If we had it all together, then we could do it. And yet, I'm not so sure that that's always true, and I wondered if you have really looked at that assumption that we would be better off, and are there examples of it, if it's regulated, for example, at state level compared to now where we have many jurisdictions?

Broadhurst: That's a good comment. I don't really think that state management of the shoreline is the answer. I think there's a tremendous amount to be said for local control and ability to have some flexibility. I think what happens though, and it's the same thing with critical areas ordinances that are at the local level, there can be so much variability. Some variation is OK, but what concerns me is that we'll have some impacts on this 30 miles of shoreline and they don't know what's happening above their jurisdiction's line. And so there needs to be some sort of complement, I think, of some entity that is looking more holistically at the whole picture. Maybe just a permit tracking system for the entire Sound, or something along those lines. I'm not sure, there certainly are no easy answers here, but I appreciate what you're saying.

Panelist Comment: I think that the issue here, and if you look at it in this way, it might change our perspective. The resources that we're trying to protect here, the resources that are supported by the nearshore marine habitat, are sort of public trust resources. They are fisheries and wildlife resources which, basically, belong to the whole state, and what the local jurisdictions are trying to do is to manage their local land-based resources, which they perceive as within their jurisdiction. So there is a conflict that we haven't resolved yet.

Broadhurst: There were several shoreline managers who I talked to who really wanted to know more about the nearshore and they just didn't have that habitat expertise, so I think that whatever we can do to help those folks who don't have that sort of training could go a long way.

Q: Ginny, just really quickly, I'm wondering whether it makes sense to introduce the "W" word, "watersheds," to this conversation in thinking of the answer to Doug's question about the best jurisdiction. I haven't heard it in this conversation, which is sort of unusual these days. Is there a way of organizing or thinking about nearshore on some landscape ecosystem watershed scale.

Broadhurst: One of the recommendations that came out through our work group report was to make sure that the nearshore is included in watershed process, so that whoever is looking at a watershed analysis or managing at the watershed level would go beyond the water's edge, and I think that's important, but again that still slices it up. There still needs to be somebody who's looking at the whole basin of Puget Sound and that shoreline. So, look at it both ways, I guess.

Freidman-Thomas: I was struck by the difference on what your first pass using GIS produced for you in terms of the distribution and the lack of connectivity of your priority restoration sites vs. what you came up with once you went into the field. And I would like to ask about your thinking about that seeming disparity.

White: There are two reasons for that. The most obvious reason is that the sewer plant had already identified a lot of the sites in the center of that area. And the other reason is that I don't yet know and our GIS team does not yet know how to program connectivity into a query for sites. In other words, you have attributes in a table, but I'm not sure, I think there is a spatial analysis tool that is now available for GIS, it's at low level GIS, which is what we're using, that you can use to identify the proximity of sites and that was a filter that wasn't applied. And so what we did is we used a human element to apply that filter in developing the second plan. That was not used.

Q: Do you know what could be achieved with the final vision? Do you have selling point to say, if we were able to restore all of these wetlands, we would never have a flood in the Snohomish River again, or anything along outrageous statements like that?

White: Actually, we'd probably be more likely to predict flooding protection than things like gain in salmon number. I was asking about that yesterday in another session. I think that if we could somehow identify numbers of wildlife or numbers of fish gained per unit restoration effort, we'd go a long way toward getting money for projects.

Q: Have you measured salinity to provide information on water movement in the breach area and have you investigated sediment loads going out into the system after the breach occurred?

A: Yes, we've been taking some salinity measurements. We've got some sediment stations that we have installed with the help of Si Simenstad and Wendy Morrison of the Louisiana Marine Consortium. We also have a number of volunteer efforts going on with Adopt a Beach looking for *Spartina* invasions. We have the Black Hills Audubon Society following and tracking migratory waterfowl making new use of the mud flats. We feel it's appropriate to involve as much of community outreach as we can to attract these. We have vegetation transects, both permanent and some rotating, that we've been looking at changes in the system as the tidal inundation is becoming more and more. But it's just one breach of 10 to 12 that need to be done in order for the system to start to return.

Q: Ginny, you mentioned that there were 50-odd jurisdictions. It seemed like what you were crying out for was integrated coastal zone management to bring together the parties, the stakeholders. I'm with Fisheries and Oceans in Canada, and my name is Steve Samis. Our minister is, according to the Oceans Act, to lead and facilitate in integrated coastal area management on the three coasts of Canada, and that would seem to say to me that we, as a federal body, are responsible for providing that point of leadership. And I think on of the places where we're going to focus will be Georgia Strait. And presently we have the same mix of jurisdictions that you have. And from your experience in Puget Sound, could you offer us some advice on how to begin this integrated coastal zone management in Georgia Strait?

Broadhurst: I'm not really sure how to answer that question. I think one thing that's true in the Puget Sound area is that there are certainly pros and cons of having local jurisdictions have a considerable amount of authority over their own shoreline. This area has always had a strong local control and so I guess what I am calling for is that coordinated system to evauate effects rather than what I think is piecemeal right now. I think in any sort of integrated process, it's really important to make sure that the local jurisdictions are comfortable with and understand the reasons for the management. Around here, I think if we had the federal government or the state government just come in and say this is what you will do, and there's no ifs ands or buts, that wouldn't work real well. So I think you have to divvy up the management responsibilities so that everyone understands why you're doing what you're trying to do and as I mentioned I think that that education piece of why you're doing that, you know, these regulations are important because these are the marine resources that use this area and we're trying to protect those and make sure that your populace really understands that that's your mission.

Comment: My name is Jim Johannesson with Coastal Geologic Services. I just had a question or a comment following up on some of the ideas we're heard about management levels, local, we've got obviously state, and others, federal and of course we've go the private homeowners level which is so important for nearshore habitat and many of the other things that we've talked about. But there's one other level that I haven't heard talked about that's slowly coming out which his neighborhood and/or subdivisions and/or local community groups and/or ten homeowners that happen to live next to each other. And as there's more and more education out there, people become aware of the impacts they're having, the need to satisfy permit requirements, that they can't act alone in a 50-foot stretch. I think that's one thing we need to further through another approach, another way to manage these. Well, all the people that want to hear from government, well talk to your neighbors. And that's more affordable for them, it's more effective. It's also more effective from the resource standpoint. Trying to minimize erosion, water quality, drainage impacts, things like that.

Broadhurst: Jim, you didn't tell everybody what you do, which is he's done a series of really successful workshops working with landowners. And I think you've probably had a lot of success in having those sorts of projects work. I've found, in talking with some of the local shoreline managers, that while they have it on the books that they encourage joint use of docks or joint stairways, those sorts of things, they have a really hard time making it work. And I'm not sure why. Whether it's just a liability question or they haven't really had the time to bring everyone together to explain why it would be helpful of not. I

hope we can get towards those sorts of solutions.

Johannesson: It's certainly not a cure all and there are a lot of neighbors it's not going to work with, but when it works, it works well, and it's great to have an existing structure, but it isn't always required.

D. Peeler: I just wanted to extend my appreciation for the work that you've all done in identifying these tools, coming up with the information and the plans, really, for these critical nearshore and estuarine areas. It's really great. We've known how critical these are to wildlife for several years, a really long time, but we haven't had this kind of information to help push that ahead in the public arena. But I do have a question for Jacques. You talked about the Snohomish Estuary Plan, there, and I know it's probably a little early in the public review process and so on to get some sense of how you think that's gong to be received. That would be one question. And the kind of partnerships that you might be able to form to get some of those areas into the system. But have you looked at the expense yet, or the costs of the proposals that you've generated here?

White: No, because that is really contingent on whatever value a particular landowner is going to put on their land. The restoration projects are really not terribly expensive. It'd be probably in the hundreds of thousands of dollars to liberate some of those 200 to 300 acre parcels of land by breaking dikes. The land acquisition is an interesting issue and the prices vary depending on what people think the market will bear for those properties. I can't go beyond that. I don't know. Jim Kramer, who along with a large number of different groups, is developing a program to identify restoration targets within the Puget Sound basin. Not necessarily just restoration, but restoration and acquisition targets throughout the watersheds in the Puget Sound basin, is guessing at a billion dollars to restore fish and wildlife habitat in the Puget Sound basin over the next ten years if we want to be successful in preventing EPA listings. The Snohomish, I don't know. I'd guess we're talking tens of millions of dollars at least.

D. Peeler: Yes, it seems like it's going to be a big number, a hard one to beat around the Sound. Obviously, looking at a combination of conservation easement type of purchases as opposed to outright land purchases can maybe help to defray part of that cost, and I think in a lot of cases people might be willing to enter into that kind of agreement. But you know as well as I do that it's a long road to get there. Thanks.

[ii] In Canadian terminology, refers to alternative siting and procedures to reduce impact

[ii] Refers to what is usually called mitigation in US policy language

[1] Defined as the area from 200 ft above ordinary high water mark down to the shallow subtidal.