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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The papers presented in these proceedings have not been peer-reviewed, and the graphics and references in these papers are presented much as they were submitted originally by the authors.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

SESSION 4B

URBAN INFLUENCES ON WATER QUALITY-ELLIOTT BAY AND DUWAMISH ESTUARY MONITORING AND ASSESSMENT

Session Chair:
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King County Department of Natural Resources

Use of a Risk-Based Decision Process in the Design of CSO Control Strategies for an Urban Estuarine Watershed

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Introduction

The King County Department of Natural Resources is conducting a Water Quality Assessment for the Duwamish River and Elliott Bay, which lies in an urbanized, industrialized watershed in Seattle, Washington. The purpose of the Water Quality Assessment is to provide information for making decisions about the future of King County's combined sewer overflow (CSO) control program. This effort was motivated by the State of Washington's adoption of a long-range standard for CSO control of one uncontrolled overflow per discharge point in a year of average rainfall. The long range planning process for wastewater treatment in King County has estimated the cost of achieving this standard to be $600 million.

The first objective of the Water Quality Assessment is to understand the existing conditions of the Duwamish River and Elliott Bay in terms of level of risk to aquatic life, wildlife, and people who use this estuary. Under this objective we want to answer the following questions:

- What populations of aquatic life and wildlife live in this estuary?
- How many and what types of people use the estuary, and how do they use it?
- What concentrations of chemicals are present in the water and sediments and living tissues that could harm aquatic life, wildlife and people (the receptors)?
- What other physical and biological stressors are present in the River and Bay that could harm these same receptors?
- What is the level of risk to these receptors from chemical, physical, and biological stressors in the system?
- Which stressors are the most significant?

A second objective of the Water Quality Assessment is to understand the significance of CSO stressors compared to those from other sources. The following questions will be addressed under this objective:

- What proportion of chemical, physical, and biological stressors in the river and bay result from CSOs?
- How much will aquatic life, wildlife, and human health risks be reduced by elimination of CSOs?
- Which stressors are the most significant?

A third objective is to facilitate stakeholder input to key decisions on where and how to focus regional efforts to protect the river and bay.

The fourth objective is to provide a tool for watershed-level assessments. Under this objective we want to answer the following questions:

- Can risk assessment be used in identifying the most significant stressors in a watershed?
- Can a hydrodynamic model for the estuary be extended for use throughout the watershed?

The final objective is to provide a scientific basis for decisions on project prioritization and control technologies utilized for the County's CSO control program.

Methodology

The methods for ecological and human health risk assessment designed by the US Environmental Protection Agency (EPA 1989; 1992; 1994, 1996) and the Water Environmental Research Foundation (Parkhurst et al. 1996) are being used to describe potential risks to aquatic life, wildlife, and people who use the Duwamish River and Elliott Bay, and how the risks could change with control of CSOs.

A model that predicts the concentrations of chemical stressors and other potential changes in the water body will drive the risk assessment. The model is essential to predict conditions in the estuary if CSOs are eliminated. The model also provides a way to fill gaps in data on current conditions. A sampling program that allows model calibration and detailed characterization of the physical, chemical, and biological stressors entering the Duwamish River/Elliott Bay ecosystem supports the modeling effort.

Stakeholder Committee

The project team recognized early that to achieve our objectives, a major component of our work would be focused on supporting, educating and listening to people from the region who have a stake in the outcome. We also realized that because this is a complex project, in which highly technical information will be used to make policy-level decisions, it would be necessary to work with a committed group of stakeholders from the beginning to allow them to learn the process and be able to provide significant input.

Who are the Members?

The committee includes 28 individuals from government agencies, Native American tribes, community councils, environmental groups, businesses and industries. This committee includes individuals who work in the environmental field and are technically able to advise the project team, as well as community leaders who are aware of the issues and share a vision for how the resource could be in the future. The quality of the project and the usefulness of the final product will be much greater because of the involvement of this committee from the beginning.

What is the Role of the Committee?

The role of the committee is to (1) provide input to the design of the risk assessment and (2) provide recommendations to King County on key decisions that are discussed in the next section.

What Process was Developed to Give and Receive Input?

Work with the stakeholder committee has centered on full-day workshops with the whole committee, and half-day working sessions with a technical subcommittee of self-selected members, interested in participating in greater depth on a specific topic. To date we have held three full-day workshops and five half-day working sessions. Additional working sessions are scheduled monthly through project

completion. The first workshop described the project and the role of the committee. We also asked the members to describe in writing their vision for the Duwamish River and Elliott Bay, which was subsequently helpful in developing the management goal and guiding the selection of assessment endpoints. The second workshop focused on the problem formulation and receiving input on the assessment endpoints. In the third workshop we presented the plan for the risk assessment and asked the stakeholders for help obtaining information about how people use the estuary. The fourth workshop will be held in April and will be two full days. At this workshop the results of the risk assessment will be presented and the stakeholders will develop their recommendations to King County regarding the CSO control program.

Risk Assessment

Why Risk Assessment?

The challenge for King County was to find an approach to this assessment that would allow us to quantify and characterize the harm that may be occurring to aquatic life, wildlife, and people who use the resource; and how the likelihood of that harm would be changed with the control of CSOs. The process of ecological and human health risk assessment provides such an approach.

Dialogue with King County Management and the Department of Ecology resulted in agreement that a risk assessment approach would provide a means of describing the benefits to be achieved by controlling CSOs. The outcome of the CSO assessment may demonstrate that the benefits of control are significant; alternatively, it may show that the expected benefits will be minor. In either case it is expected that the assessment will help identify project priorities and appropriate CSO control technologies that maximize improvements to the study area.

What is the Goal for the Duwamish River and Elliott Bay?

The first task in planning for a risk assessment is to develop a management goal for the resources being assessed. In this Water Quality Assessment, the resources are the lower Green and Duwamish River and Elliott Bay. The WQA project team and consultants using information heard at the Stakeholder Workshop in November 1996, as well as information from King County Managers developed the following management goal:

> Design a CSO control strategy whose goal is to continuously protect and improve water, sediment and habitat quality. Indicators of achieving this goal are abundant, diverse and healthy biological communities and enhanced recreational, commercial, and cultural use of the resources.

Decisions will be made by the King County Executive, King County Council and the Washington State Department of Ecology after considering the recommendations of the regional stakeholders. The Stakeholder Committee for this project will submit a written report containing recommendations on CSO control to the King County Executive. The ultimate decision-maker will be the Department of Ecology.

There are a series of decisions that will be based on the outcome of this study. These include answers to the following questions:

- Is the CSO contribution to human and ecological health risks significant? Why or why not?
- If the CSO contribution is not significant, what should be the next steps for the CSO control program?
- If the CSO contribution is significant, what CSO control scenario does King County recommend to the Department of Ecology? Are there other recommendations on how to meet the management goal for this estuary?

Water Quality Modeling

The water quality assessment team has opted to create a mathematical model of the Duwamish Estuary and Elliott Bay that will predict where chemicals from various discharges travel in these water bodies. The Duwamish River-Elliott Bay model has two components. The first is a hydrodynamic model that describes the water flow; the second is the chemical and bacteria fate and transport model that describes the addition, removal, movement and behavior of chemicals and bacteria in the study area including those that reach the sediments.

The model will be run with CSO inputs as they are now, to represent current conditions, then run again without CSO discharges. The physical area covered by the model includes the Green/Duwamish River from the Interstate 405 bridge to the outer bounds of Elliott Bay near Alki Point. The model divides this area into 500 cells, and divides the depth into 10 layers; thus, the model can realistically simulate how chemicals from the CSOs and the other sources are distributed to 5,000 locations within the Duwamish River and Elliott Bay estuary ecosystem.

Field data were collected to support development and verification of the model. Data collected to support the water flow portion of the model included Elliott Bay and Duwamish River information from water level sensors, meters that measure the speed and direction of water movement, and automated meters that record water temperature and salinity. The chemical and bacterial portions of the model were developed and verified with data taken from 39 water stations on a weekly schedule of non-storm samplings and more frequent sampling associated with storms. Most of these stations were grouped adjacent to CSOs, with three surface/subsurface pairs of stations located across the river. A station was located upstream of the study area to measure inputs to the study area from the river and a corresponding station on the Puget Sound boundary of the model. At these stations measurements were taken for conventional parameters such as nutrients and oxygen concentrations, as well as bacterial numbers, metals, and organic chemical concentrations. Sediment analyses included concentrations of metals, organic chemicals, and physical characteristics such as sediment particle size.

A crucial piece of information in the building of a fate and transport model concerned with CSO impacts was the collection of CSO samples during storm events. Automated samplers were installed in five of the most active CSOs in the study area. These samplers collected water samples both as sequential discreet samples and as composite samples. These samples were analyzed for the same parameters as the water and sediments and the data used as CSO inputs to the model.

To ensure the model provides accurate information to the risk assessment, the model coefficients were calibrated to accurately predict study area hydrodynamics and field data concentrations. The calibrated model was verified with an independent set of field data to test its performance under a different set of conditions. The calibrated and verified model is used to predict how chemicals from various sources are transported through the Duwamish Estuary and Elliott Bay, providing a surrogate for a large-scale field-monitoring program for estimating chemical concentrations at particular sites for use in the risk assessment.

Using Model Output in the Risk Assessment

The successfully calibrated and verified model will be used to estimate chemical concentrations in the water column and sediments throughout the study area. The current conditions and zero-CSO concentration data will be used in the risk assessment to estimate direct exposures to water and sediment-borne stressors. The differences between stressor concentrations under these two situations will give an estimate of the CSO contribution to the chemical and bacterial concentrations in Duwamish River and Elliott Bay waters and sediments. The differences between risks estimated for current and zero-CSO conditions will represent the CSO contribution to risks.

The model will not be used to estimate tissue concentrations in fish, shellfish, and invertebrates that could be eaten by aquatic life, wildlife, or people. Instead, exposures from eating seafood will be estimated

using tissue concentration data from fish and crabs collected in the study area. The model will be used to estimate the reduction of fish and shellfish exposures under the zero-CSO scenario relative to current conditions. This will provide an estimate of the CSO contribution to risk from seafood consumption.

Estimating Risks

Risks to people will be estimated for two pathways: (1) direct contact with chemicals and pathogens in Duwamish River and Elliott Bay sediments or waters, and (2) exposure to chemicals or pathogens from eating seafood or incidentally ingesting sediment or water. We will estimate risks for a variety of exposure "scenarios" to try to represent the range of human uses of the estuary. The chemical exposure estimates will be compared to toxicity reference values and slope factors developed by the U.S. EPA to estimate whether and which chemicals from CSO and non-CSO sources are potentially causing risks to people. Pathogen exposure estimates will be compared to minimum infective dose estimates from the scientific literature to assess the potential pathogen risks.

Risks to wildlife will be estimated using methods similar to those for estimating risks to people. The exposure pathway to be assessed in the wildlife risk assessment is exposure to chemicals from ingesting prey and Duwamish River and Elliott Bay waters. Exposure estimates will be based on a combination of site-specific data and wildlife exposure factors (things like how much food wildlife eat, the areas over which they range, etc.) taken from the scientific literature. The exposure estimates will be compared to toxicity reference values derived from the scientific literature, to estimate whether and which chemicals from CSO and non-CSO sources are potentially causing risks to wildlife. The wildlife risk assessment will use probabilistic methods to estimate and evaluate the uncertainties about wildlife exposure levels and toxicity reference values. The wildlife risk assessment will also evaluate changes in habitat or water quality parameters (i.e., changes due to sedimentation or scouring, decreases in dissolved oxygen levels, increases in water temperature, or decreases in salinity) that adversely affect wildlife use of the Duwamish River and Elliott Bay.

Potential risks to the aquatic ecosystem from exposures to physical and chemical stressors will be assessed by comparing peak sediment and water concentrations, by location, to a distribution of toxicity reference values (concentrations at which specifically defined toxic effects begin to occur) representing different aquatic taxa, using the methodology of the Water Environment Research Foundation (WERF). The results will be estimates of the fraction of aquatic taxa potentially at risk at each location, compiled to form a probability distribution of the percent taxa potentially at risk. The advantage of the WERF methodology over a traditional "risk ratio" (i.e., exposure concentration divided by toxicity reference value) is that the distribution of percent taxa potentially at risk is a more meaningful interpretation than a risk ratio. The former indicates the consequences (i.e., the percent taxa potentially at risk) of observed exposure levels, whereas the latter simply indicates the factor by which observed exposure levels exceed threshold concentrations (i.e., a sensitive species' toxicity reference value), without information about the ecological significance of the observed exceedances. In addition to estimating risks by the WERF methodology, water column and sediment bioassay and benthic community survey data will be assessed to provide additional lines of evidence regarding the level of potential risk to the aquatic ecological community due to CSO and non-CSO sources of physical and chemical stressors.

Conclusion

We have completed the field sampling, configured the model, and prepared the data for entry into the model. We have had three of five workshops with the stakeholder committee and two of three workshops with the WERF peer review panel. We continue to hold working sessions with the stakeholder committee on a monthly basis. Current plans are to complete the Water Quality Assessment of Elliott Bay/Duwamish River in mid-1998.

Once the Water Quality Assessment is completed, King County will work to better resolve non-

CSO (stormwater runoff, non-stormwater point sources, existing sediment contamination, and groundwater) source contributions to risks in the Duwamish estuary. In addition, the County intends to conduct a risk-based evaluation of specific source control scenarios using the water quality model. The application of similar risk-based decision processes to other management problems in the Duwamish estuary and other King County watersheds is being considered at this time.

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Public Outreach and Stakeholder Involvement for King County's Combined Sewer Overflow Water Quality Assessment

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Introduction

Public outreach and stakeholder involvement are critical to the success of most projects. This paper shares some of the outreach approaches used as part of King County's Combined Sewer Overflow (CSO) Water Quality Assessment (WQA) for the Duwamish River and Elliott Bay. Hopefully, this information will assist other organizations in establishing public outreach and stakeholder involvement for their own watershed projects and programs.

Project Background

The Duwamish River and Elliott Bay form a complex estuary that has changed significantly since the mid-1800s due to human activities. The waterbodies support often incompatible uses of commercial, industrial, and residential development, as well as numerous point and non-point pollutant discharge sources. In addition, the Duwamish River contains a fluctuating salt/fresh water wedge, which adds additional challenges to modeling the estuary.

The purpose of King County's undertaking of a water quality assessment in this estuary is two-fold: to determine existing conditions in the water bodies through sampling, monitoring, and computer modeling of the water column and sediments; and to understand the relative significance of CSO pollutants compared to other pollutant sources by studying CSO impacts on human health and aquatic life through a risk assessment. The results of this assessment will help in prioritizing King County CSO projects, possibly extending or decreasing the CSO program's timeline in completing projects, and revising the program to look at other issues such as sediment remediation. In addition, the results may assist in the development of a watershed management strategy, could lead to changes in Washington State's CSO legal requirements, and may provide a framework by which other agencies can develop water quality and risk assessments in their own jurisdictions.

Public Outreach and Stakeholder Involvement

Public outreach and stakeholder involvement involves gaining public support (or at least avoiding antagonism) for your project. How do you successfully obtain support for your project? Through the following means:

- Marketing,
- Education,
- Involvement, and
- Communication.

The above items are not completely independent processes, but instead they overlap. For example, a brochure can be both a marketing tool and an educational tool. Each of these items also requires internal and external coordination.

Marketing

Marketing is a word and action that tends to be avoided by government agencies—and yet in the world of today, marketing is a pivotal tool for garnering interest for your project. Marketing has to occur before the next steps of educating, informing, and asking for input can take place. For many projects, you may find that there is a large overlap between marketing and education. This is particularly true of government projects where you need internal and external support for your project, but external support may not be actual "direct" payment for the service or information you are providing.

In terms of King County's projects, the marketing techniques we found useful included:

- Logos and/or slogans,
- Information materials,
- Surveys,
- Presentations, and
- Media involvement.

Logos and Slogans

A logo and/or slogan developed for a project will ensure immediate project recognition as well as provide consistency across all project documents. They can also be used as part of your letterhead, on brochures, covers of documents, etc. Just as in marketing products, logos and slogans provide instant project recognition on both conscious and unconscious levels. King County's Department of Natural Resources (DNR) continues to use the highly successful, "Clean Water—A Sound Investment." This verbal play acknowledges Puget Sound as one of the major water bodies under DNR protection as well as the idea that protecting water quality makes sense (cents!).

Information Materials

To help people learn about your project, develop materials that both introduce people to the project and also educate them on the goals and expected results of the project. Fact sheets and brochures are a great means to "get the word out on your project" and can be easily handed out or mailed to people. Colorful graphics attract attention, but should not be too slick. The use of recycled paper enhances DNR's goal to clean up our environment.

Surveys

For the CSO WQA, King County conducted a survey both to market and to introduce people to our project; to obtain specific information from a larger group as input to our project; to build a mailing list of people and organizations interested in the project; and to aid in the development of a stakeholder group. The survey also helped to focus our mailings to people who would be interested. If at all possible, conduct a survey that is statistically valid. This is more expensive and time-consuming, but adds a greater level of validity to your data.

Presentations

Presenting papers at meetings and conferences is a great way to gain recognition for your project. This type of recognition tends to also help you gain future funding and support from supervisors, managers, and staff within your agency and from other agencies. This is particularly important if you expect to have "spin off" studies and projects which need policy and budgetary support.

Media Involvement

Getting positive press on your project, on television and in newspapers can be very helpful. For the CSO WQA, we undertook a dye study of the Duwamish River to obtain a better understanding of how discharges mix with the river currents. This was covered by three news stations and by at least one local newspaper. This is the type of marketing that managers particularly like because it reaches the greatest number of people.

Education

Once people know about your project, you may want people to have a better understanding of why you are doing the project and what the project entails. Education tools include:

- Web sites,
- Newsletters, and
- Events.

Web Sites

Now that we have entered the age of the Internet, development of a web site can reach a different audience. Once the site is developed, it can be fairly easy to update. A web site also supports the marketing of your project. The same information you use to update your web site can be sent in the form of short articles to community newspapers (or vice versa).

Newsletters

To educate people and keep them updated on your project, a monthly or quarterly newsletter is also helpful. These same newsletters can be handed out along with brochures at community meetings, open houses, and other forums in which you are giving a presentation.

Events

Most of the time, open houses, community meetings, and other types of meetings are used as forums to educate the public. Besides these types of events, also try to develop events that people can actively participate in as part of your project (e.g., tree plantings). For the CSO WQA, we conducted boat tours of our study area for our stakeholder group. These tours gave people a better understanding of the complexity involved in the project and allowed for a more interactive and fun forum to share information and thoughts on the project.

Involvement

Some projects stop at the marketing and education stages. However, more projects are finding it necessary and extremely helpful to more actively involve the public and special groups. Involvement is one of the most difficult tasks of any organization. Some of the external challenges that organizations find it very difficult to overcome when trying to contact people include: busy lifestyles, a barrage of information on a daily basis, lack of trust for the organization, and the difficulty of developing "sound bites" of information on very complex issues. There are also internal institutional barriers as well. For example, "Do you really want to hear and can you act on information that may have not been scoped in your project timelines and budgets?!"

As discussed by David A. Julian, et al., in "Citizen Participation—Lessons from a Local United Way Planning Process," many times citizen participation is defined as *any* effort to collect input from citizens. But at the same time, citizens are not truly given the power to influence decisions. This leads to a situation in which citizen participation in decision-making is based on consultation and not on genuine power to influence. Thus, in developing your public outreach plan, be clear in

terms of what you can and want to do: consultation or direct participation. These are not mutually exclusive and may overlap. However, do not ask for or imply you want direct participation if you only want consultation. This can cause anger and create a situation where people feel their input is tokenism and therefore their commitment is meaningless. **For the most part, commitment and trust only exists when people feel they can achieve something through the process.**

For involvement, King County used two approaches:

- Consultation, and
- Direct Participation.

Consultation

This type of involvement can be very helpful and includes the more general feedback (e.g., opinions, questions) received at public, community, and more general meetings or through phone or written surveys. Information from this form of participation helps you gauge how successful you are at communicating your message, rather than making any substantial changes to the information your message is based upon. Consultation can help with the "spin" you desire your information to take. For the CSO WQA, consultation will take place after the study is completed and results are documented in an easily accessible format.

Direct Participation

With direct participation, you must be willing to make changes to your project based on feedback from participants. If accepted and used, direct feedback from an informed and committed group of individuals who are actively following the progress of the project can be extremely helpful. For the CSO WQA, we developed two groups to help the project: a peer review panel and a stakeholder committee. **For each group, it was important to define roles and expectations of the members very early in the process. It was also important to indicate when and how their specific input was needed within the overall schedule of the project.**

Peer-Review Panel

The Peer-Review Panel for the CSO WQA consists of members of the Water Environment Research Foundation. This panel included national experts in risk assessment, modeling, toxicology, and wet weather issues. The role of this committee is to provide input on the development of the risk-assessment plan, to review sampling data, to advise King County staff regarding potential problems and improvements that could be made to the project, and to provide input on how other jurisdictions nationwide are handling their own assessments. The Panel also provides additional oversight and information to the project as well as an evaluation of the overall project once it is completed. Peer Review Panel input is mainly received via phone calls, e-mails, and comments received on documents. Their input proved to be helpful in refining many aspects of the project. For the CSO WQA, Peer-Review-Panel input will be included in a separate Peer-Review Panel Report.

If possible, it is helpful to have at least one meeting where stakeholders and peer review panel members are able meet each other face to face. The Peer Review Panel adds a level of objectivity to your project that may render your project more valid in the eyes of the public and the stakeholder committee.

Stakeholder Committee

The Stakeholder Committee was developed based on responses to a survey, specific interests that King County staff knew existed within the study area, as well as recommendations from the other stakeholders. The final group consisted of representatives from businesses, community councils,

environmental groups, tribes, and other government agencies.[i] The diversity of the group in terms of interests, background, and technical expertise was a major strength. The committee's major roles include providing input on the design of research activities and the development of the risk assessment portion of the project as well as making recommendations to King County on several major policy issues based on the results of the study. Because of the wide diversity of knowledge and opinions, this group has been very helpful in refining the project. In addition, members of the stakeholder committee would question each other's opinions, which proved to be helpful in situations where it was awkward for the County to refute certain information. This group was also developed to help us disseminate information to a wider audience (the groups they represent) than we ourselves could do on a regular basis. More technically inclined members of the stakeholder committee also formed a Technical Subcommittee and greatly helped staff resolve specific technical details related to the project.

For the CSO WQA, we had several full-day workshops and offered additional working sessions in which we shared recent information more informally. We also kept the stakeholders updated by mailing draft and final copies of reports, meeting minutes, and other materials.

When directly involving people:

- Keep them frequently informed,
- Remind them of upcoming meetings and workshops,
- Keep them interested and happy, and
- Formally recognize their contributions.

Frequently Inform Committee Members

Between formal meetings, there is a lot of work that is undertaken on projects. Keep people frequently informed through newsletters, meeting minutes, and informal working sessions. By keeping people in the loop throughout the process in addition to major meetings, people will have a better understanding and higher level of commitment towards your project. In addition, at the end of the project people will be more prepared to make recommendations and support the methodology and results of your project as they *trust the work and the people involved in the project.*

Remind Members of Upcoming Meetings and Workshops

Meetings should be set up far in advance, as people's calendars fill quickly. Also, phoning and e-mailing people one to five days before the actual meeting takes place to remind them of the date and time increases meeting attendance.

Keep Members Interested and Happy

When conducting meetings, develop the agenda so that there is room for discussion (not only presentation) of the information presented. Try to respond less in defending your project and engage more in active listening and recording of people's comments and issues. Be sure to develop questions that allow people to directly share their expertise and give something to the project. In addition, information should be mailed out for review for meetings at least two weeks before the meeting, so that they can participate more actively in meetings. Overall, the more active the participation from the committee members (versus passive listening of presented information), the happier, more interested, and committed the members will be to the project.

Also, find fun ways to involve committee members such as field trips of your project area with a team member sharing specific information on the project on site. For the CSO WQA, we arranged boat tours of the estuary, which proved to be fun and educational.

You will know your stakeholder process has been successful if:

- A variety of interests are represented on the committee.
- The members share information with their groups.
- Committee members attend meetings and actively comment on processes and products.
- Members actively discuss issues and share differences of opinion.
- Members support the project in other ways[ii].
- Members are willing to support "spin-off" projects.

Formally Recognize Members' Contributions

The more members feel that their contributions are incorporated into the project, the more committed and supportive the members will be of the project. Recognition includes: follow-up letters after formal meetings responding to how members comments are being addressed within the project, notations within meeting minutes responding to members comments, and addressing issues through e-mail and phone conversations.

In addition, to ensure that stakeholders contributions are formally noted in the process and by decision-makers, hire consultants to work with stakeholders in developing a stakeholders recommendations report. This report can include majority and minority opinions.

At the close of the project or if your project has a major meeting around a major holiday (e.g., Christmas or the New Year), with approval of your organization, be sure to give something to your committee members as a thank you gift. Gifts can include T-shirts and mugs printed with your project's logo and slogan or a certificate of appreciation. These gifts also keep stakeholders aware of your project outside of specific meetings.

Communication

Communication is the underlying component of all the previous items. Graphic and verbal communication are just as important as written communication. Gestures, body language, and tone of voice may be the most important aspects of communicating. For example, 93% of what we communicate to people is unspoken (7% is words; 38% is tone; 55% is gesture/body language).[iii]

Verbal Communication

When conducting workshops and meetings, be sure to have a person who has strong facilitation skills leading the session. These skills include the ability to: limit people who talk too long or who digress from the topic, get people to speak who remain silent, gauge when it is time to move to the next topic, and to calmly and effectively deflate disrupters.

Also include a person who records comments and issues on flip charts as well as someone taking notes. This ensures that staff is actually taking in what people are sharing. Review the notes after the session and follow-up by phone or letter with committee members or the public in terms of how the issue is being addressed. Responding to comments goes a long way in developing trust.

When responding to issues raised with high emotions, respond with respect and empathy. Avoid defensiveness or trying to prove the person wrong by spouting additional technical data. The person rarely moves from their stance with this type of response. Your main goal should be to diffuse the anger, fear, and outrage. This can be done by keeping a relaxed body and empathetic facial expression. Use expressions such as "This sounds very important to you," "Thanks for sharing your thoughts and feelings," and "That sounds like a difficult situation." *Always respond with sincerity and avoid technical and unsympathetic responses.*

Graphic Communication

Graphic material can greatly aid in presenting very complex technical or detailed information. For example, after the CSO WQA second workshop there was a high level of committee confusion regarding roles, responsibilities, and when input would be expected within the project's timeframe. This confusion was eliminated at the third workshop after we developed a wall- and handout-sized graphic timeline. PowerPoint has also been helpful in developing presentation materials (e.g., overheads, slides, or for using your computer for the presentation). It also helps to save time as handouts are created at the same time as presentation materials.

When developing colored graphics, ensure that they will work as black and white versions as well. This allows handouts to be more legible and cost-effective to produce.

Conclusion

Public outreach and stakeholder involvement continues to be one of the most challenging aspects of many projects. It is important to use marketing, education, involvement, and communication techniques in a pro-active and sensitive manner. The positive recognition you achieve for your project, the trust you build with the public and other organizations, or at the very least the ability to get your project implemented with fewer delays, will more than make up for the time and expense involved in undertaking public outreach and stakeholder involvement.

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[i] One of the challenges of the Stakeholder Committee was that it remained in a certain level of flux. Not all members could make all meetings or some of the major meetings, some left and were replaced during the project's schedule, and some stakeholders sent substitutes if they could not attend a meeting or if the stakeholder wanted to send someone with more expertise or interest on particular topics.

[ii] Several members in our stakeholder group supported the project in other ways. For example, some shared additional studies that might be of interest to staff and some lent their services; one stakeholder and his colleagues at the National Marine Fisheries Service analyzed bile from English sole collected jointly by King County and the Washington Department of Fish and Wildlife. This information will be used by the three organizations in an attempt to predict bioeffects from exposures to PAHs in the water bodies in the CSO WQA study area.

[iii] Information presented at the opening session presentation at the Pacific Northwest Conference for Women in Seattle, WA on September 30, 1997.

Simulating Water Quality in the Duwamish Estuary and Elliott Bay: Comparing Effects of CSOs and "Other Sources"

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Introduction

King County owns and maintains the wastewater treatment plants and the large conveyance pipes that carry the wastewater for Seattle and most of the smaller cites within the county boundaries. In parts of the conveyance system, the system is connected to both sewage and stormwater lines in what is termed a combined system. During periods of dry weather the conveyance system transports mainly sewage to the treatment plants. When the county experiences a significant rainfall event, the capacity of the conveyance system is exceeded thus forcing combined sewage and storm water to overflow into the local water bodies surrounding Seattle. These sites are termed combined sewer overflows (CSO). CSOs only discharge when the ability of the conveyance system to transport sewage is exceeded due to the rainfall event. Currently the largest number of CSOs are in the Duwamish Estuary; hence the focus of this study is in the estuary (See Figure 1).

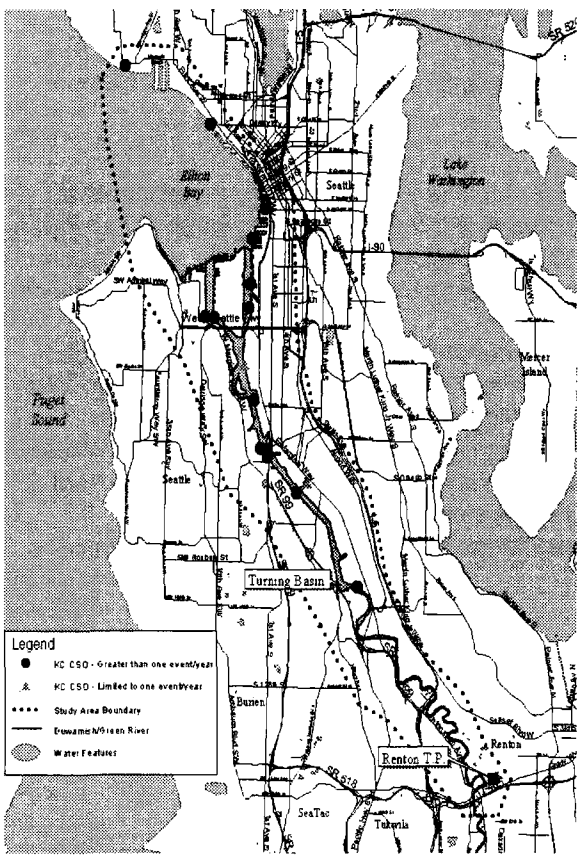

Figure 1. WQA study area

The Department of Ecology (DOE) requires the county to keep records on the number of discharges, volume of overflow, and chemical content of CSOs as part of the National Pollution Discharge Elimination System (NPDES). King County made agreements with DOE to reduce the number of CSO discharges from all sources to one untreated event per year, without a specific deadline for achievement of this standard. Federal standards allow four to six untreated discharges per year.

As part of the county's commitment to maintain or improve water quality, it embarked on the task to determine how significant CSO discharges into the Duwamish Estuary are compared to other contaminant sources that discharge into the estuary as well. The project, called the Water Quality Assessment (WQA), looks at the risk to human health and aquatic life as it exists today and what it would be without CSOs discharging into the estuary. To assess risk, the county is using chemical concentrations in the water, sediments, and aquatic life (primarily fish). Values for the water and sediment chemical concentrations will be obtained from a computer model that has been calibrated against observed field data.

Chemicals of Potential Concern

Eutrophication is not a problem in the Duwamish Estuary and Elliott Bay. Sampling of dissolved oxygen (DO) revealed that DO concentrations were always above 7 mg/L, even during CSO events. Flow through the estuary is rapid enough such that no other eutrophication processes pose significant risk to aquatic life. The chemicals that are of potential concern (COPC) in the estuary and bay were selected based on availability of data, water and sediment standards, and those known to inpact the health of humans or aquatic life. The COPCs modeled in this risk assessment are:

- Metals: Arsenic (As), Cadmium (Cd), Copper (Cu), Lead (Pb), Nickel (Ni), Zinc (Zn), Mercury (Hg), Tributyltin (TNT);
- Organic compounds: 1,4 Dichlorobenzene, 4 Methylphenol, Bis(2 ethylhexyl)Phthalate, Fluoranthene, Phenanthrene, Total PCB, Pyrene, Benzo(k)Fluoranthene, Chrysene, Benzo(b)Fluoranthene;
- Fecal coliform bacteria.

Use of a computer model for the WQA study is twofold: 1) it will be used as a mass balancing tool to estimate chemical contributions from other sources given CSO, ambient, and boundary chemical loads, and 2) it will be used as a surrogate field sampling program. This paper discusses how the model was prepared and applied for the WQA risk assessment.

The Duwamish Estuary

The Duwamish Estuary is located in the heart of Seattle's industrial area southwest of downtown, and flows north into the southern tip of Elliott Bay. It is a heavily used shipping port and is a significant habitat area for salmon and other wildlife. The estuary is defined as the body of water starting from the mouth at Elliott Bay to 18.5 km upstream. Most of the estuary is dredged for shipping with dredging extending approximately 12.5 km upstream from the mouth. The mean river flow is about 42.5 cubic meters per second (cms) or 1500 cubic feet per second (cfs). The estuary is well stratified (salt-wedge type) when fresh-water inflow rates are greater than 28 cms (1,000 cfs); but when flows are less than 28 cms, the lower 5.5 km of the estuary grades into the partly mixed type. Cross-channel distribution is generally uniform for a given location and depth. Salinity migration is controlled by tides and freshwater flow. The upstream extent of the wedge is dependent upon fresh-water inflow and tide height and can range from 2–16 km upstream from the mouth. Dye studies indicate that downward vertical mixing over the length of the salt-wedge is almost non-existent.

Freshwater flow into the estuary comes from the Green River. The river is regulated at the Howard Hanson dam for flood control. However, flow rates do vary considerably day to day because of storm runoff and snow melt. Upstream tidal flow reversal has been observed in the Green River 21 km upstream of the mouth.

Water depth in the dredged sections of the estuary vary from 15 m at mean lower low water (MLLW) at the mouth to 3.6 m at 14th Ave bridge (9.5 km). The channel above the turning basin is not dredged and varies in depth from 1 to 2 meters (MLLW). Elliott Bay, at its deepest location, is about 150 m (MLLW). Tides in the Duwamish have ranged from –1.4 to +4.5 m from mean lower low water. Freshwater flow from the Duwamish discharges into Elliott Bay causing a freshwater lens atop the saline waters in the bay.

Modeling Objective

The objective of the modeling program was to use the computer model as a mass balancing tool to determine mass loading contributions from sources other than CSOs. The model was then used to assess the differences in resulting water and sediment concentrations due to CSOs and "other sources." These differences could then be used in a risk assessment process to quantify the risk to humans and aquatic life from CSOs relative to "other sources." Therefore, it was assumed that there are three basic chemical sources in the estuary: boundaries, CSOs, and "other sources". King County had limited financial

resources and limited its scope of work to collecting information on CSO chemical compounds and ambient chemical concentrations. Knowing two of the three sources, the computer model was employed as the third equation to estimate inputs from the other chemical sources.

Computer Model Description

King County selected the Environmental Fluids Dynamic Computer Code (EFDC) developed by Dr. John Hamrick for application to the WQA modeling. It was selected over other models because it can simulate highly stratified flows and both nutrients and toxic compounds. It has been applied to many estuarine studies, and it is non-proprietary. The county reviewed 13 different models for application to the Duwamish. They were rated against a set of requirements (defined by the county) that were based on the needs of the WQA and observed conditions within the estuary (See Walton, 1998).

EFDC is a curvilinear-orthogonal, three-dimensional hydrodynamic-chemical transport and fate model. The hydrodynamic and transport modules are coupled. The vertical dimension is transposed into a stretching coordinate system where cell layers move with the free surface. Hydrodynamics are solved using the depth integrated momentum equation and employs a turbulent-intensity and length-scale transport equation to solve for turbulent viscosity and diffusion. Transport and fate is solved using the mass transport equation and incorporates a near field model which can be coupled to the mass transport model. For a detailed explanation of the model derivation see Hamrick (1992).

The study area was segmented into 500 cells in the horizontal plane, and ten layers in the vertical for 5,000 cells in total. The EFCD model was modified to simulate near-field CSO effects within the larger model cells, and to simulate chemical fate equations as a function of the physical and chemical state of the estuary and bay.

Field Monitoring Program

Water velocity, elevation, temperature, and salinity were collected during the field-monitoring program. Acoustic doppler current meters were used to measure water velocity. Three meters were deployed in the estuary and two in Elliott Bay. The meters measured the horizontal and vertical components of the water velocity. Velocities were measured at half-meter intervals in the estuary and at 4-meter intervals in Elliott Bay. Salinity, temperature, and water elevations were measured at three field stations in the estuary. Two stations had two instruments placed one meter below the surface and one meter above the bottom. The third station had a single instrument placed one meter below the surface.

To determine the feasibility of an intense field sampling program, King County did a pilot study to see if it was possible to collect the number of samples required and if current laboratory analytical techniques were appropriate. The pilot study revealed that most of the organic compounds were non-detects and the saline water of the estuary significantly interfered with measuring metals. The County instigated new laboratory procedures to remove the saline matrix from the water samples, also lowering the detection limit by an order of magnitude. To overcome the inability to measure organic compounds using conventional laboratory procedures, Semi-Permeable Membrane Devices (SPMD) were used. The SPMDs were deployed for two weeks and provide a time-averaged estimate of water concentrations over the deployment period. Organics were still sampled using conventional methods approximately once per month and except for bis(2-ethylhexyl)phthalate, all other organic COPCs were non-detects.

The field-monitoring program was started October 31, 1996 and ended June 4, 1997. Approximately 26 sampling trips where performed during this time period. Samples were taken either once or three times per week. If the three largest CSOs were not discharging (non-storm event), one sample was collected for that week. If the three CSOs were discharging (storm event), then sampling occurred over three consecutive days. Personnel were put on 24-hour alert, seven days a week, to mobilize for storm sampling. For safety reasons, it was decided that sampling would only occur during daylight hours. Because of this, some storm sampling trips did not commence until the tail end of the storm period when CSOs had slowed considerably.

Sampling locations were selected along the length and width of the estuary, see Figure 2. Samples were taken one meter below the surface and one meter above the bottom at most river sites. Samples were taken 15 to 20 m below the surface in Elliott Bay. Samples were taken at three locations across the river at most of the river sites. The parameters measured are listed in Table 1.

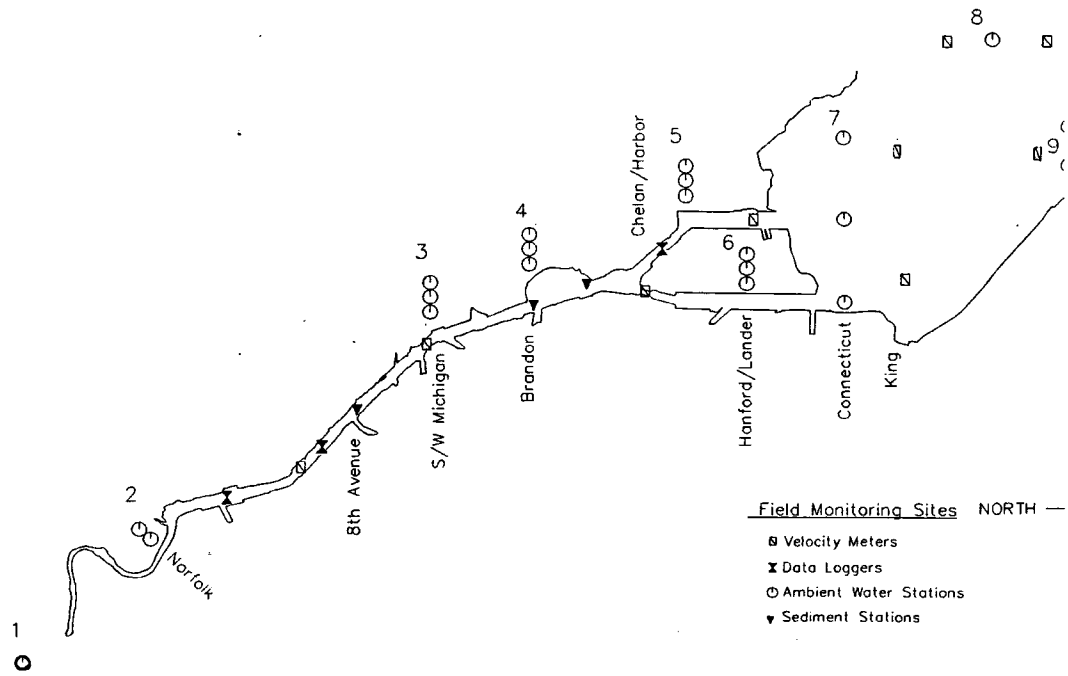

Figure 2. Locations of sampling and field instrument sites.

Table 1. Quantities measured for COPCs.

Chemical of Concern	Measuring Technique	Measured Quality	
		Water	Sediments
Metals:	Standard		
As, Cd, Cu, Pb, Ni, Zn	Analytical Methods (SAM)	T,D	T,TOC,TS
Organic:			
1,4-Dichlorobenzene,	SAM	T,D,TVS	T, TOC,TS
4- Methylphenol,	SAM	T,D,TVS	T, TOC,TS
Bis(2-ethylhexyl)Phthalate,	SAM	T,D,TVS	T, TOC,TS
Total PCBs,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Pyrene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Benzo(k)Fluoranthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Fluoranthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Phenanthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Chrysene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Benzo(b)Fluoranthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Others:			
Mercury	Ultra-Clean	T,D	T,TVS
Fecals	Methods	T	
Tributyltin	SAM	TAT	
Total Suspended Solids	Mussels	0.45	PD
	SAM		

T = Total Concentration; D = Dissolved Concentration; = TOC Total Organic Carbon; TS = Total Sulfides; TVS = Total Volatile Solids; TAT = Total Time Averaged Concentration; PD = Phi Size Distribution; 0.45 = 0.45μ Filter

CSO contaminant concentrations were obtained by sampling five of the largest CSOs that discharge along the Duwamish. They were Brandon, Connecticut, King, Hanford, and Chelan Regulators. The sampling program was designed to test whether chemical concentrations changed over the duration of the discharge event (first flush effects), whether they varied between CSO outfalls, or whether they varied across the depth of the CSO pipe. Additionally, previous testing results were available for the Denny Way CSO site regarding chemical analysis, solids settling, and how metals partition to suspended solids.

Sampling QA/QC

Collection of water samples was started before the County had developed the analytical techniques to remove the saline matrix from the samples. The new technique lowered detection levels an order of magnitude below what was previously achievable. While this was good, it also proved to be problem. The lower detection limit increased the degree to which sample contamination could be observed. Standard QA/QC revealed significant field blank contamination had occurred in most samples for lead, copper, and zinc. The sample values were subsequently blank corrected using the limited information that was available.

Model Configuration

John Hamrick from TetraTech Inc. configured the model with assistance from King County staff.

Elliott and Duwamish Boundary Conditions

At the model boundaries, Elliott Bay is forced by a phased harmonic tidal series. The Harmonics and phasing were determined from water-level time-series data taken near Fourmile Rock and Alki Point. The phasing accounts for the time it takes the tidal wave to travel across the boundary length. At the upstream I-405 Green River boundary tidal effects are minor. Conditions at the Green River boundary were driven by fresh water flows obtained from the US Geological Survey (USGS) flow station at Auburn. Daily average flows were used.

Chemical data gathered from the field monitoring program at the Tukwila and Duwamish Head field stations were used at the Green River and Elliott Bay boundaries respectively for model calibration. Boundary conditions for the one-year and ten-year simulations were generated from a simple stochastic model developed from observed data. Correlation analysis of the Tukwila data indicated a significant relation between zinc, lead, and copper, but less so with nickel. No significant correlation existed for arsenic and cadmium. Analysis of the Duwamish Head data at the 20-m depth indicated a correlation between cadmium, copper, and arsenic. Analysis of all data indicated no significant correlation between river flow, rainfall, or CSOs. Data generation for both boundaries entailed generating a primary constituent with the same statistical properties as the observed field data, and then generating the other constituents from the primary, maintaining the observed correlation.

CSOs

Currently 13 King County CSOs discharge into Elliott Bay and the Duwamish Estuary. Hydrographs used for the calibration are from flow data recorded over the 1996–'97 year. Hydrographs for the ten-year runs were generated from the county's basin run-off and hydraulic routing models and historical rainfall data from a recent ten year period. The rainfall periods were matched to the historical Green River flow data at the Auburn station.

Analysis of the chemical data from the CSO monitoring program indicated that there were was no significant change in concentrations over the duration of the discharge. Concentrations appeared to vary over the depth of the pipe, and there were subtle differences in concentrations between a few of the CSOs and a few of the metals of concern. As a result, average concentrations for each of the five CSOs for each of the COPCs were used in the model. For the remaining seven CSOs that were

not monitored, concentrations were estimated from one of the five CSOs based on similar basin characteristics; see Appendix A for grouping and concentrations.

Other Sources

The actual number of other sources that discharge into the Duwamish Estuary and Elliott Bay are unknown. However, an estimate of total run-off into the estuary was modeled using the County's basin run-off model. The county currently maintains a basin run-off and conveyance model for the Westpoint and Renton treatment plants to estimate sewer flow through the pipe network. The model is calibrated to observed flows in the sewer conveyance system and includes effects from stormwater inflows generated by rainfall. The portion of the storm water from impervious-area flow that does not enter the sewer system was considered to drain into the storm system. Run-off flow was routed along basin drainage lines and discharged into the Duwamish and Elliott Bay as another source. Forty-one discharge hydrographs of storm water were generated from the run-off model.

Chemical input for the other source loads was obtained from historical stormwater data. Since the intent of the modeling was to estimate chemical loads from other sources, stormwater chemical concentrations were adjusted until model predictions were comparable to observed data. Exact concentrations were not required, only reasonable estimates were needed. Use of the stormwater data does not imply all loads from "other sources" are solely from stormwater drains. The review did not provide stormwater chemical data for some of the COPCs. In these instances, CSO data was used. Appendix A summarizes initial chemical conditions for other sources.

Sediments and Suspended Solids

Sediment concentrations from Elliott Bay and the Duwamish were obtained from the DOE SedQual database. This data set was supplemented with data collected from the WQA. Sediment particle size for the bay and estuary was obtained from GeoSea Consulting, which gathered the data for the Elliott Bay/Duwamish Restoration Program. This data was also supplemented with particle information collected by Science Applications International Corp. (1991) for the US Army Corps of Engineers (ACOE) dredging at the turning basin. Very little sediment chemistry and particle data information is available for the Green River section of the model. A small amount of particle size information was obtained from an in-field assessment of percent fines at four locations by county technicians, as well as anecdotal evidence from the USGS. The data was collated to initialize sediment concentrations and particle distribution within all model cells. Multiple points within a single cell were averaged into a single value. Cells with no data points were interpolated from neighboring cells.

Review of all the sediment and CSO sampling data indicated that the sediments could be divided into three general classes, fine sand to course silt, silts, and fine silt to clay. Solids concentrations at the Green River boundary for fine sand/course silt class were generated using the Corps of Engineers Suspended Solids Loading Equation (ACOE 1981). Concentrations for the finer solids were generated from a similar regression equation using Total Suspended Solids (TSS) field data collected for the WQA and USGS Auburn flow data. The field-monitoring program provided suspended solids concentrations for CSOs. Solids concentrations for other sources were obtained from existing stormwater studies.

Chemical Properties

Chemical partition values for the metals As, Cu, Cd, Pb, Ni, and Zn were estimated from field data using the following equation (Thomann 1987),

Equation 1

$$P = \frac{c_T - c_d}{c_d m}$$

Where: P is the partition coefficient
c_T is total chemical concentration
c_d is dissolved chemical concentration
m is total suspended solids concentration

An average partition coefficient was computed for each sample site and the sample averages were

combined to compute a single partition coefficient. A constant partition coefficient was used for all chemicals. However, sample averages indicated that partitioning varied along the length of the estuary. An attempt was made to develop a regression equation to explain the observed relation between salinity and the partition coefficient, but none of the equations proved to be statistically significant. Chemical partitioning for the organic compounds, tributyltin, and mercury were obtained from literature references (Hamrick 1998).

Chemical decay rates for the organic compounds were obtained from literature references (Howard et al. 1991). Minimum rates were used for both water and sediment columns. A zero decay rate was used for unlisted chemicals. Partition and decay values are summarized in Table 2.

Table 2. COPC chemical properties.

Chemical of Concern	Decay (1/sec)	Partition Coefficient (l/mg)	
		Water	Sediments
Arsenic	None	0.02	0.005
Cadmium	None	0.018	0.004
Copper	None	0.11	0.025
Lead	None	4.4	0.4
Nickel	None	0.042	0.01
Zinc	None	0.082	0.02
Tributyltin	None	1.0e-3	Same
1,4-Dichlorobenzene	None	8.1e-5	Same
4- Methylphenol,	None	2.4e-6	Same
Bis(2-ethylhexyl)Phthalate	3.5e-7	4.8e-3	Same
Fluoranthene	3.1e-6	9.8e-3	Same
Phenanthrene	7.7e-6	8.4e-4	Same
Total PCBs	None	2.2e-3	Same
Pyrene	9.4e-5	3.4e-3	Same
Benzo(k)Fluoranthene	3.9e-7	3.0e-1	Same
Chrysene	1.5e-5	2.1e-2	Same
Benzo(b)Fluoranthene	2.7e-7	1.5e-1	Same
Mercury	None	4.4e-4	Same

Model Calibration

John Hamrick calibrated the hydrodynamic portion of the EFDC computer model and sent the calibrated model to King County staff for the mass calibration of the COPCs.

Sediments

The first constituent to calibrate was the suspended solids component. The only parameter adjustment was the suspended solids settling velocity. While the model requires specifying a critical sediment stress at which resuspension occurs, no field measurements were made to estimate a critical stress value. Instead literature references were used as suggested by Hamrick (1.6×10^{-4} [m/sec]^2 non-cohesive and 1×10^{-4} [m/sec]^2 cohesive). At first, two sediment types were selected, fine sand and silt. Sediment samples from ACOE (SAIC 1991) pre-dredging studies indicated that most of the solids deposited in the turning basin are fine to medium sands. A third solids class was added with a settling velocity similar to clays and flocculated material due to the fact that too much sediment was settling out. The solids in the CSOs were also divided into silts and clays, with the same settling velocities as those used in the river.

Settling velocities and solids loads at the Green River boundary were adjusted for all three classes until an optimum fit between observed and predicted solids concentrations was reached. The best fit occurred with a suspended solids distribution at the Green River boundary of 78% fine sands, 15% silts, and 7% clays, and 100% clay at the Elliott Bay boundary. Suspended solids from CSOs and other sources were negligible compared to that from Green River. Final settling velocities

for each class was 0.01 m/sec for the fine sands, 0.004 m/sec for silts, and $1x10^{-6}$ m/sec for the clays. The final calibration graph for TSS at the Brandon site are shown in Figures 3 and 4, for the surface and bottom levels.

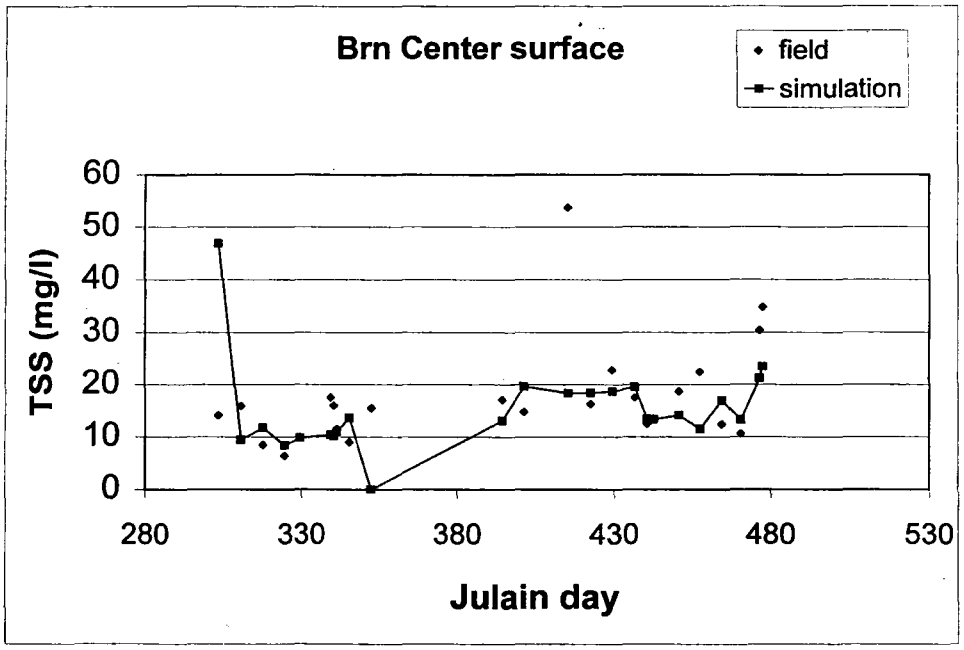

Figure 3. Calibrated total suspended sediment concentration one meter below the surface.

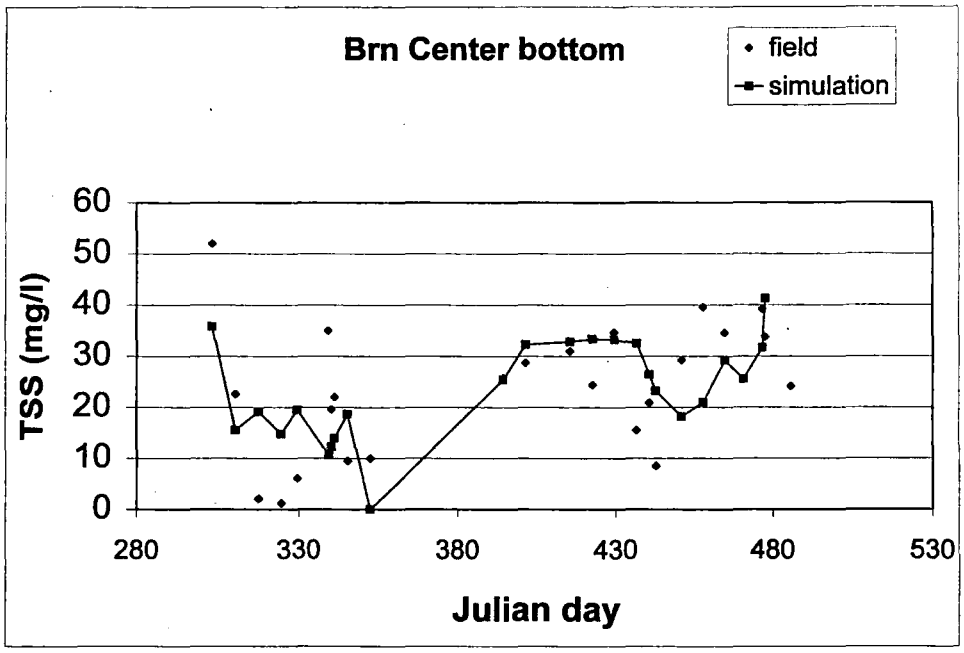

Figure 4. Calibrated total suspended sediment concentration one meter above the bottom.

Metals

Metals were calibrated after the sediment calibration was completed. Calibration entailed

adjusting load inputs from "other sources" until simulated metals concentrations were comparable to observed data. Metals loading from CSOs were not adjusted, since it was assumed that inputs from CSOs had been adequately defined in the sampling program.

The model simulated the transport of metals in two phases, dissolved and particulate. Division between the two phases was defined by the partition coefficients given in Table 2 and the suspended solids as given by equation 1. It was assumed that the partition coefficients remained constant in both space and time. Given that the partition coefficient does not vary, and that the suspended solids field has been defined, differences in simulated and observed metals concentrations were ascribed to other source loads. The model simulates chemical loads using a hydrograph and chemical concentration time series. It multiplies the flow rate by the chemical concentration to give a chemical flux into the cell. To adjust the load that discharges into the cell, either the flow rate or the chemical concentrations can be manipulated. For the EFDC model it is easier to manipulate the chemical concentration time series rather than the hydrograph.

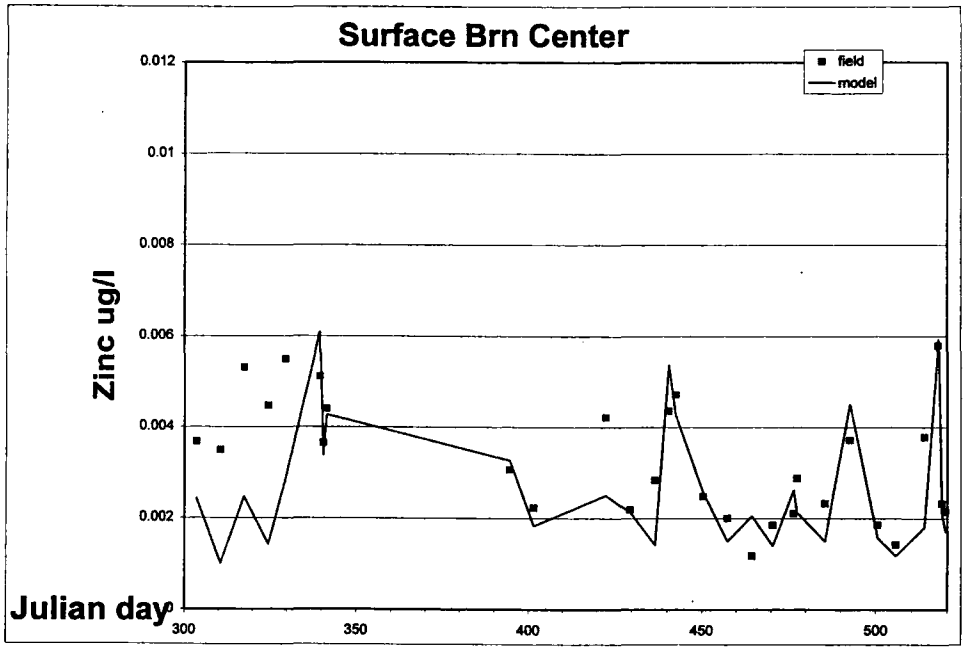

Figure 5. Calibrated total zinc water concentrations one meter below the surface.

Calibration was carried out in a series of steps, each step refined the previous steps. The first steps were to match the general fit of model predictions to field observations. After the general fit was completed, the next steps refined model predictions at specific points in the observed time series. This entailed adjusting either the existing hydrographs, chemical time series, or adding a separate hydrograph and chemical time series as needed to match observed field data. Final calibration graphs for zinc at the Brandon site, one meter below the surface and one meter above the bottom are shown in Figures 5 and 6.

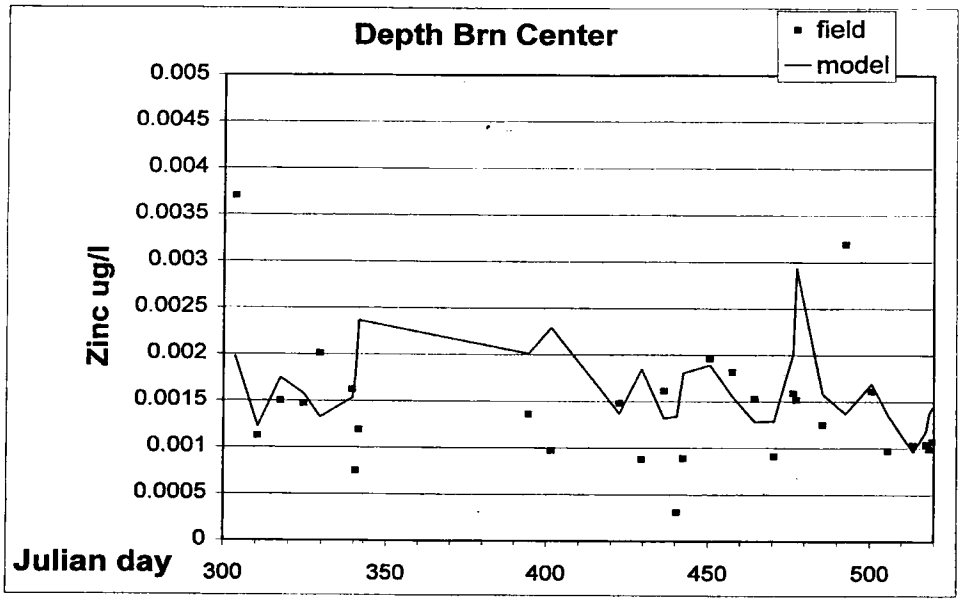

Figure 6. Calibrated total zinc water concentrations one meter above the bottom.

Organic Compounds

The organic compounds were calibrated using sample data from mussels and SPMDs. The concentrations in the mussel tissue were converted to average concentrations in the water column that would approximately result in the sampled tissue concentration. Concentrations in the SPMDs were placed in the water for two weeks. The concentrations of contaminants in the SPMDs were converted to average water column concentrations that would result in the SPMD values. Data from the model was saved and averaged over the time periods that the mussels and the SPMDs were in the water.

Calibration Results

Final chemical concentrations for other source inputs are listed in Table 3. Final CSO concentrations are shown in Table 4.

Results of Modeling

The calibrated model was run for one-year and ten-year periods. The one-year period simulation looked at differences between CSOs and other sources in the water column and estimated differences in the sediment column. Chemical concentrations were saved every hour for every model cell. The ten-year period was run to verify or correct the one-year sediment estimates. The ten-year run was necessary because of the generally slow response of sediments to loading changes, and it was not known if current sediment concentrations were in equilibrium with the existing environment.

Model results for the one-year simulations with and without CSOs have not been evaluated at the time of writing this paper. Therefore, a comparison of the impacts between CSOs and other sources has not been done at this time. However, the calibration process did reveal some information about the models' ability to simulate the highly stratified conditions in the estuary, and the relative influence of boundary sources to observed metals concentrations. The model is able to give a reasonable simulation of contaminant transport through the estuary, and the results are being used to perform a risk assessment on the impact of CSOs relative to other sources.

Table 3. Final chemical concentrations for other sources.

Metals							Organics	
Other Sources				Eastside Inputs				
Source (mg/L)	Arsenic	Cadmium	Copper	Lead	Nickel	Zinc	TBT	Phenanthrene
Pre-Julian day 400	4.64	0.95	22	22.8	0.0	134	0.0	1.44
Post-Julian day 400	3.9	0.95	22	10.8	0.0	70.8	0.0	1.44
			Westside Inputs					
Pre-Julian day 400	4.64	0.9	22	26.2	7.1	156.8	0.0	1.44
Post-Julian day 400	3.9	0.9	22	20.9	7.1	114	0.0	1.44

Organics

Source (µg/L)	Chrysene	Fluoranthene	Pyrene	1,4-Dichloro benzene	4-Methyl phenol	Benzo(b) fluoranthene	Benzo(k) fluoranthene	Total PCB
Eastside Inputs	0.06	0.43	3.59	0.15	2.32	0.015	0.0005	0.0
Westside Inputs	0.06	0.43	3.59	0.15	2.32	0.015	0.0005	0.0

Table 4. Arithmetic mean chemical concentrations for CSOs.

Metals (µg/L)								
Arsenic	Cadmium	Copper	Lead	Nickel	Zinc	Mercury (ng/l)	TBT (ug/l)	
2.87	0.51	32.78	30.68	8.24	130.17	26.95	0.0	
Organic (µg/L)								
Total PCB	Chrysene	Fluoranthene	Phenanthrene	Pyrene	1,4-Dichloro benzene	4-Methyl phenol	Benzo(b) fluoranthene	Benzo(k) fluoranthene
0.0	0.242	0.43	0.439	0.363	0.382	5.62	0.239	0.208

Summary

The Duwamish Estuary and Elliott Bay is a highly stratified flow system where CSOs and other sources tend to discharge into the system. The EFDC model adequately simulated the stratified flow and transport of metals and organic compounds through the estuary and into the bay, maintaining observed chemical differences between the fresh water lens and the saline wedge. Assessment of the calibration process indicates that the most influential source of arsenic and cadimum is from Puget Sound. The Green River is the primary source for nickel.

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Overview of Water Quality Assessment Biological Sampling Program

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Introduction

King County's researchers recently conducted extensive biological sampling in the Duwamish River estuary to evaluate risks to aquatic life, wildlife, and human health from combined sewer overflows (CSOs) and other discharges. This effort was undertaken between September 1996 and December 1997 using a number of specialized sampling and analytical approaches. Field sampling to measure chemical concentrations in water and sediments occurred over essentially the same time period. Upon completion of analyses, these data will be used to validate model-based estimates of chemical concentrations. These data also will add to our basic knowledge of the Duwamish River estuary and serve as a baseline for future monitoring. While some preliminary results are available and will be discussed in other sections of this conference, most of the resulting data are still to be analyzed and interpreted. This paper, then, focuses on the design of biological sampling and how the results will be used to predict risks.

The biological sampling program consisted of the following components:

- Chemical bioaccumulation studies in transplanted and wild mussels
- Chemical bioaccumulation studies in fish and shellfish
- Microbial uptake studies, and
- Benthic infaunal studies.

Chemical Bioaccumulation in Transplanted and Wild Mussels

Chemical bioaccumulation in transplanted and wild mussels was studied to learn which chemicals entering the Duwamish River estuary were bioavailable and bioaccumulated, and if bioaccumulation changed seasonally. Measured chemical concentrations (metals, organics, and tributyltin [TBT]) in the soft tissues of mussel transplants (*Mytilus galloprovincialis*) and wild mussels (*Mytilus trossulus*) was the basis of chemical monitoring. Following the general recommendations of Salazar and Salazar (1995), mussel transplants were deployed at two combined sewer overflow locations (Brandon Street CSO, Duwamish/Diagonal Way CSO/storm drain) and at two in-river reference sites (Slip #1, Kellogg Island) (Figure 1). Additionally, mussel transplants were deployed at a reference site in South Puget Sound (Totten Inlet). At each CSO location, the mussel transplants were deployed immediately in front of or just below (down river) of the discharge pipe. Distance from the outfall to the transplants was 25 m or less. Wild mussels were collected from the same CSO/storm drains and in-river reference sites as well as other locations in the Duwamish River (Slip #4, Hanford Avenue CSO, Terminal 105) and in Elliott Bay (Elliott Bay Pier). Wild mussels were collected within 50 m of each CSO location. These studies were undertaken in the dry season (September 1996) and repeated in the wet season (March 1997). Some

preliminary results are presented by Strand et al. (this volume).

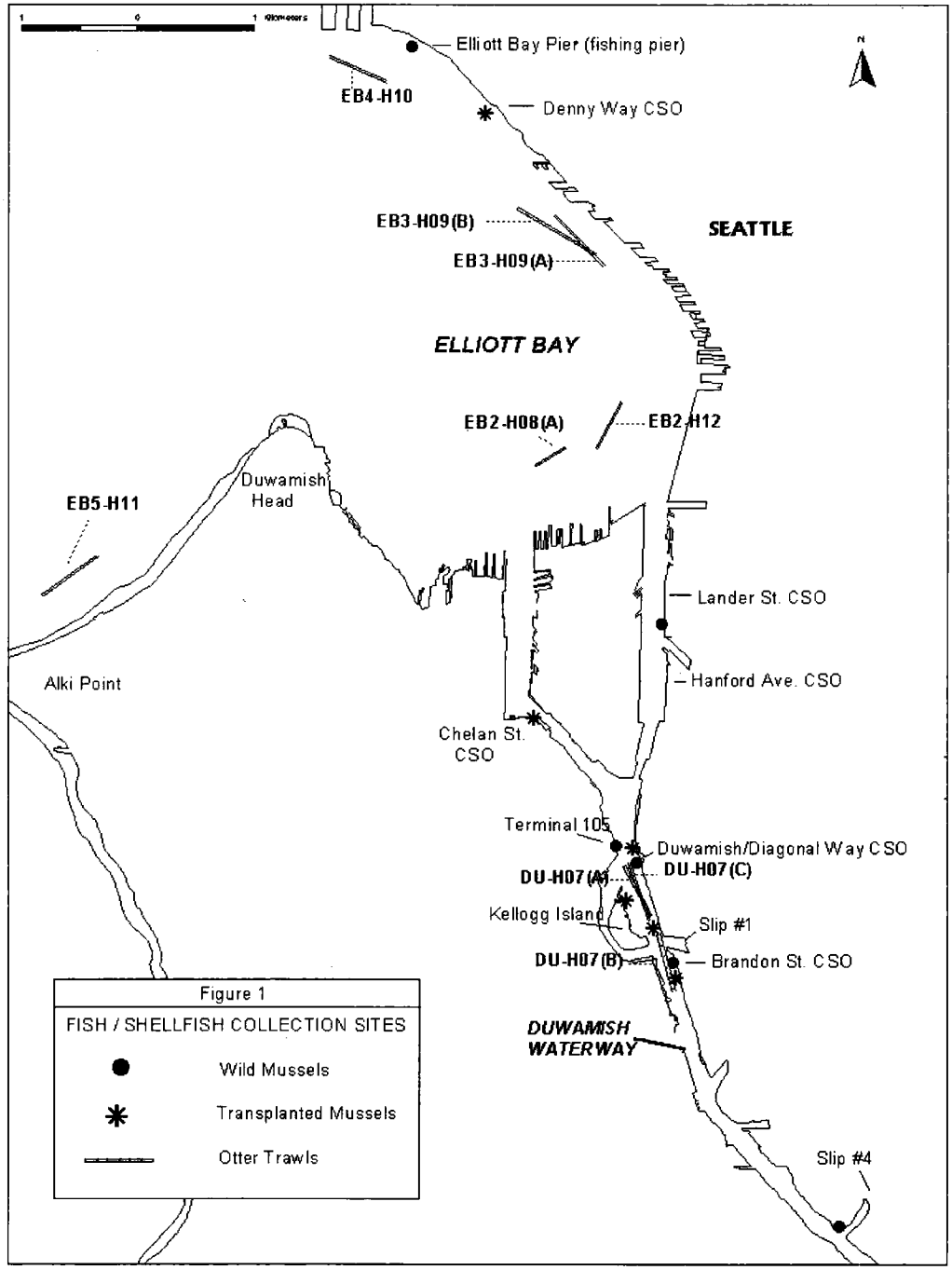

Figure 1. Site map of study area with sample locations.

Data on bioavailable organic chemicals were also collected in the wet season by employing semi-permeable membrane devices (SPMDs). Following the methods of Lefkovitz and Crecelius (1995), these devices were deployed in concert with mussel transplants at two of the CSO locations (Brandon Street CSO, Duwamish Diagonal Way CSO/storm drain) in the Duwamish River. Chemical

concentrations in SPMDs and mussels can be used to calculate concentrations of organic chemicals in the water column averaged over the period of exposure when the concentrations of organic chemicals are too low to detect using traditional grab sampling methods. Data from both the SPMDs and mussels, along with data from water and sediment monitoring, are being used to calibrate King County's computer model for simulating the transport and fate of organic chemicals from CSOs and other sources in the Duwamish estuary.

Chemical Bioaccumulation Studies in Fish and Shellfish

Concentrations of metals, organics, and TBT were also measured in fish, shellfish, and invertebrates (other than mussels). These measurements will be used in estimating chemical doses to wildlife and humans from ingesting chemically contaminated prey/seafood, sediment, and water from the study area. Estimated chemical doses from all sources in the Duwamish estuary will be used to calculate risks to wildlife and humans. Species monitored included English sole (*Pleuronectes vetulus*), quillback rockfish (*Sebastes maliger*), shiner perch (*Cymatogaster aggregata*), Dungeness crab (*Cancer magister*), spot prawn (*Pandalus platyceros*), market squid (*Loligo opalescens*), and intertidal invertebrates, mostly amphipods (*Traskorchestia traskiana*).

Fish, crabs, and prawns were collected by King County and the Washington Department of Fish and Wildlife employing a 400-mesh eastern otter trawl in April 1997. Trawl locations in the Duwamish River and Elliott Bay are shown in Figure 1. Reference collections were made in Port Susan and in Hood Canal. Intertidal invertebrates were screened from intertidal sediments in the Duwamish River at Kellogg Island and from a reference location at McAllister Creek on the Nisqually National Wildlife Refuge in July 1997. Squid were caught by rod and reel from the Elliott Bay Pier in December 1997.

Analytical measurements of chemicals in fish and shellfish tissues will contribute to estimates of exposure for wildlife receptors, in this case spotted sandpiper, blue heron, bald eagle, and river otter. Only tissue concentrations appropriate to the type of prey consumed by each receptor will be used in determining exposure. Chemical doses will be calculated using both measured and modeled chemical concentrations in prey weighted by ingestion rates for each prey item as well as doses received from ingesting sediment and drinking water. Chemical doses will be compared to toxicity reference values derived from the scientific literature for each of the target avian and mammalian receptors. Risks associated with chemicals from all sources will be distinguished from risks associated with CSO discharges. King County's chemical transport and fate model makes it possible to estimate the chemical contributions of CSOs relative to the total chemical background at various sites within the Duwamish estuary.

Human health risks (non-cancer and cancer) from consuming seafood will be estimated following EPA methodology (USEPA, 1989). Chemical doses will be calculated using measured and modeled fish and shellfish tissue concentrations and consumption rates for different types of seafood estimated for children, subsistence, and recreational fishers. The range of consumption rates used will encompass those experienced by minority group communities whose exposures may be influenced by their cultural or social activities. King County conducted a fish consumption survey of people collecting or gathering fish and shellfish from the study area in the summer of 1997. Other relevant consumption data will be obtained from the scientific literature as well as estimates of other types of exposure to chemicals in sediments and water that can take place during human use of the estuary. Chemical doses will be compared to EPA-derived chronic reference doses and cancer slope factors to determine human health risks. Again, risks from all sources of chemicals in the study area will be distinguished from chemicals discharged from CSOs.

Some preliminary results of analyses of chemical burdens in fish and shellfish from the Duwamish estuary are included in the Poster Session of this conference.

Microbial Uptake Studies

Transplanted and wild mussels were used to monitor microbial pathogens (bacteria and viruses) in the Duwamish River. In a study conducted at the beginning of the wet season in September 1997, uptake of microorganisms in wild mussels was studied before and after a CSO overflow at the Brandon Street outfall. To gain better perspective on potential human exposure to the raw sewage component of combined sewer overflows, sewage treatment plant influent was also sampled and analyzed for the same microorganisms.

The pathogens analyzed in the treatment plant influent and in mussels included fecal coliforms, *Salmonella* spp., *Listeria* spp., and total enteric viruses. Fecal coliform concentrations were also measured in CSO discharges and in surface waters of the Duwamish River and Elliott Bay. Fecal coliform concentrations throughout the study area will be modeled using King County's water quality transport and fate model developed for this project.

Potential human health risks from pathogens in the Duwamish estuary from CSO discharges as well as from other sources will be estimated using two methods. First, modeled surface water concentrations of fecal coliforms will be compared to regulatory guidelines for shellfish harvesting and swimming for baseline conditions and for conditions which assume that no CSOs are discharging. Second, a qualitative assessment of the likelihood of risks from disease-causing bacteria and viruses in the estuary will be performed. This assessment will be based on data for pathogens present in sewage treatment plant influent, data from the scientific literature on the presence of pathogens in storm water and other sources, data from the scientific literature on survival rates of pathogens in estuarine waters, on uptake and depuration rates in shellfish, and on the doses of pathogens required to cause infection and illness in humans (ILSI, 1996; Rose and Gerba, 1991).

Benthic Infaunal Surveys

Benthic sampling was undertaken at a CSO/storm drain and a paired reference location in the Georgetown Reach of the Duwamish River. The CSO/storm drain selected for study was the Duwamish/Diagonal Way CSO/storm drain, located just upriver from Terminal 106 on the east shore. This particular CSO/storm drain was selected because it has been studied extensively by King County (1997) and clear gradients of organic enrichment (based on total organic carbon [TOC]) and sediment chemical contamination have been documented. A reference location on the opposite side of the river near the downstream tip of Kellogg Island was selected because Leon (1980) and Cordell et al. (1996) had studied the benthic community and shown that it was healthy and diverse. Sediments at the reference site were not found to violate the State of Washington Marine Sediment Quality Standards (Chapter 173-204-WAC) (R. Shuman, King County Department of Natural Resources, personal communication). The hydrodynamics, bathymetry, and conventional properties of sediments (grain size, total organic carbon [TOC]) at the reference location are similar to the hydrodynamics, bathymetry, and conventional properties of the sediments at the CSO/storm drain location.

Benthic infauna and sediment chemistry samples were collected in September 1997. Their sampling and analyses followed the Puget Sound Estuary Program protocols (PSEP, 1987; 1996a,b,c). A paired-station approach for statistical analysis will be adopted where stations within the influence of the CSO/storm drain will be compared to stations at the reference site. Station pairings will be based on similarities in distance from shore, depth, sediment grain size, and TOC. Characteristics (endpoints) of the benthic communities to be statistically analyzed will include the relative numbers and abundances of major taxonomic groups (polychaetes, molluscs, arthropods, echinoderms, and oligochaetes) as well as various diversity, evenness, trophic, and dominance indices. Additionally, these endpoints will be compared to the Puget Sound reference ranges currently being developed by the Washington Department of Ecology (Striplin, 1996).

Data from the CSO/storm drain will be compared to data from the reference site to determine whether

statistically significant changes in the benthic community end points described above occurred in areas influenced by the CSO/storm drain. These data will be correlated with the concentrations of chemicals found in the sediments at these locations as well as the conventional properties (grain size and TOC) of the sediments. Any changes in the benthic community endpoints will be used to validate predictions of risk to aquatic life (benthos) based on model-derived sediment chemical concentrations. These data also will be compared to results of recent sediment bioassays conducted at this site and at other CSO sites.

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Current Structure in Elliott Bay, Washington: 1977–1996

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Introduction

This paper describes the average water movement in Elliott Bay located off Seattle, Washington. Averaging over monthly (28-day) intervals effectively filters out the hourly and daily swings of currents associated with tides and winds. This enabled the historical current records to be combined into a conceptual flow pattern for the Bay (Figure 1).

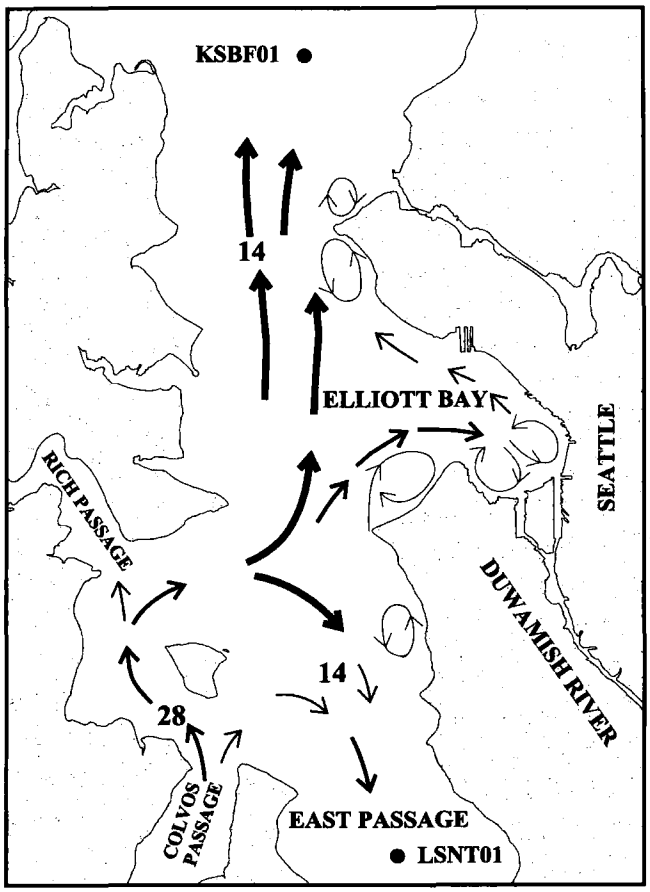

Fig. 1. Conceptual upper-layer flow pattern, Elliott Bay and approaches, ~0–50 meters. See Figure 5 for detailed flow in Elliott Bay. Numbers indicate approximate discharge in 10^3 m^3/sec. The discharge from Colvos Passage (~ 28,000 m^3/sec), largest of all Puget Sound water bodies, splits with approximately half diverging southward into East Passage and half feeding north of Alki Point. Unknown, but small transports (order of 10^3 m^3/sec) are thought to flow through Rich Passage and Elliott Bay. Permanent eddy pairs swirl north and south of Alki and West Points. Data presented in this paper suggest that an eddy pair may exist in Elliott Bay.

Historical data, together with observations of drift cards, water density, and currents made during March–June 1996 were analyzed to aid in siting an outfall from the combined sewer overflow (CSO)

located in Myrtle Edwards Park known as the Denny Way CSO. Taking additional oceanographic measurements helped refine the CSO's placement with respect to anchorage and cable areas and other facilities, including the grain terminal and tribal net pens (Figure 2).

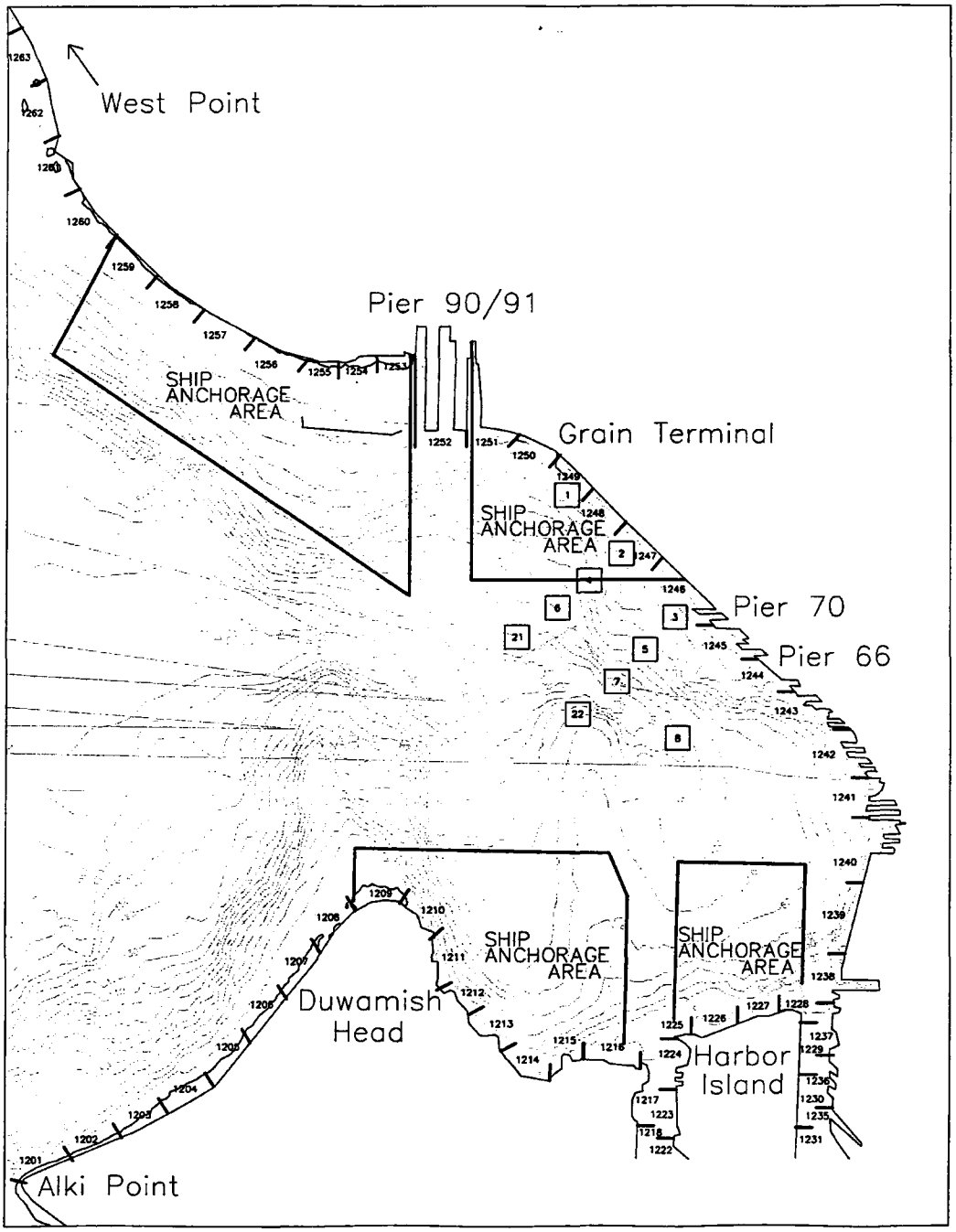

Fig. 2. Drift card release sites (squares) along the north and south transects. Two additional sites (1, 8) lying off the transects were added to obtain greater alongshore coverage. Numbers within squares indicate site designations. Ticks along shore mark 0.25-mile-long shoreline segments between Alki (segment 1201) and West (segment 1267) Points. The Denny Way CSO lies at the inshore end of the south transect (site 3).

The current meter records were partitioned into depth strata containing water arriving from three distinct sources: near-surface layer (0 to ~8 m) containing diluted fresh water from the Duwamish River; mid-depth layer (8–50 m) containing water formed in the Tacoma Narrows and

discharged through Colvos Passage; and the deepest layer (50 m to sea floor) containing water formed in Admiralty Inlet.

The movements of floating wooden drift cards, where current meters could not be placed for practical reasons, showed the movement of water nearest the sea surface. To analyze the drift card recoveries three regions were defined with respect to north-south lines drawn between 1) Duwamish Head and the Elliott Bay Marina, and 2) Alki and West Points. Inner Elliott Bay is east of (1), outer Elliott Bay is between (1) and (2), and the Main Channel extends west of (2).

A note regarding units: 3.28 ft = 1 m; 10^3 m = 1 km; and to obtain density expressed in sigma-t units, subtract one from the measured density and multiply by 1,000 (e.g., a density of 1.022 grams per cubic centimeter equals 22 sigma-t units).

Background: Effluent Behavior in Changing Climates

Previous syntheses of historical data provided a net flow diagram for Puget Sound (see Cokelet et al., 1991). Off Seattle near Main Basin's mid-channel, the flow consists of two layers, the upper layer flowing to the north and the lower layer flowing south. Effluent in the 50-m-deep upper layer travels in a few days from Alki Point to Admiralty Inlet, where roughly two-thirds of the estuarine transport exits Puget Sound into Juan de Fuca Strait. The remaining one-third is mostly refluxed downward so as to return to Alki Point in the 150-m-thick lower layer.

Effluent rises from an outfall diffuser and traps at a depth depending on oceanographic parameters and diffuser design. Water parameters include variations of density with depth and current strength in the flow layers. Previous studies indicate that the effluent from the West Point treatment plant rises into the upper layer (from 71 m [233 ft] deep diffuser, to the depth range of 30–50 meters [98–164 ft]), and effluent from the Renton outfall remains submerged in the lower layer [rises from a depth of 200 meters (656 feet) to approximately 100–150 m (328–492 ft)].

Whereas diffuser models provide reliable information on the depth ranges in which the effluent plume is trapped, depth variations of the separation between the upper and lower flow layers remain unexplored, excepting along a cross-channel transect between Meadow Point and Point Monroe (Ebbesmeyer et al., 1984). Although numerous oceanographic parameters fluctuate at decadal periods (e.g., water temperature, current variations with depth; 10 20-year period), the one which primarily determines effluent equilibrium depth—variations of water density with depth—remains reasonably steady as averaged over a year (see Ebbesmeyer et al., 1989).

Because current strength in the Main Basin's flow layers fluctuates with climate regime, the environmental data base was divided into years associated with two climatic patterns: warm and dry (WD); and cold and wet (CW; Ebbesmeyer et al., 1989). During WD intervals river runoff entering Puget Sound was below normal, water temperatures rose above 9.69 $^{-C}$, and currents in the Main Basin deeper layer flowed fastest in the depth range of 160 meters to the sea floor. During the CW intervals runoff increased above normal, water cooled below 9.69 _C, and the deep layer currents flowed fastest near 100 m (see Ebbesmeyer et al., 1989).

CW intervals occurred prior to 1926 since approximately the turn of the century, and during 1946–1977, and WD intervals occurred during 1926–1946, and since 1977 (Ebbesmeyer, et al., 1989; Table 1). To ascertain whether WD conditions persisted through 1996 current meters were deployed at the historical site during the present study and the temperatures measured during King County's monitoring program were examined.

Elliott Bay Historical Current Meter Measurements

Beginning in the late-1970s current meters were deployed in Elliott Bay in support of various environmental studies (Table 2). A single current meter record consists of current speed and direction determined several times per hour. Since the tides repeat roughly at two-week intervals, and nearly all the Elliott Bay records lasted about a month, to achieve current averages with highest

statistical certainty, the records were truncated at two 14-day intervals (i.e., 28 days). All totaled, 229 current meter records, each lasting 28 days, were available for this analysis (Table 2).

Table 1. Annual average temperature (at 150 m) in Puget Sound's Main Basin. Since 1934, water temperatures were measured monthly in the Main Basin in about half the years between 1934 and 1996. The mean values at 150-m depth for 1985–1995 were derived by averaging Metro stations KSBP01 and LSNT01 within individual months, then averaging the observations made January—December. Averages for other years are from Ebbesmeyer et al. (1989).

(a) Cold/Wet (CW) Years		(b) Warm/Dry (WD) Years	
Year	Annual average temperature (°C) (< 9.69°C)	Year	Annual average temperature (°C) (≥9.69°C)
1935	9.39	1934	9.85
1936	9.17	1938	9.69
1937	8.86	1940	10.43
1939	9.57	1941	10.61
1951	9.41	1958–59	10.10
1952	9.34	1977	10.36
1953	9.67	1979	10.11
1954	9.22	1980	10.35
1955	8.77	1981	10.67
1966	9.57	1982	10.01
1968	9.50	1983–84	10.65
1970–71	9.51	1990	9.94
1973	8.99	1991	9.85
1974	9.29	1992	10.34
1975	9.29	1993	9.84
1976	9.13	1994	10.41
1989	9.48	1995	10.61
		1996	9.92
Sample size	17 years		18 years
Mean	9.30 °C		10.21 °C
Std. dev.	0.26 °C		0.32 °C

Table 2. Sources of historical current meter data for Elliott Bay. Abbreviations: CSO, combined sewer overflow; ETS, effluent transfer system; WTP, wastewater treatment plant.

Study name	Date	Observation area	No. of current	Reference
Denny CSO	3–6/96	Northern Elliott Bay	18	This paper
Renton ETS	10/83–8/84	Inner outer southern Elliott Bay	112	URS Engineers and Evans-Hamilton, Inc. (1986)
Alki WTP	5/84–9/84	Alki Point	22	Hermes et al. (1985)
Elliott Bay Waterfront Recontamination Study	10/93–10/94	Piers 48–59	40	WA Dept. Ecology (1995), Michelsen et al. (1998)
Pacific Marine Environmental Laboratory (NOAA)	8/79–3/80	Inner and outer Elliott Bay	20	Silcox et al. (1981)
Army Corps	10/84–1/85	Four Mile Rock	3	Evans-Hamilton, Inc. (unpubl. records)
Army Corps	5/79–9/80	Harbor Island	6	L.H. Larsen (unpublished)
King County	1/97–5/97	Inner and outer Elliott Bay	8	Shuman and Schock (1997)
Total # records			229	

New Oceanographic Data

Oceanographic data collected in 1996 were of three types:

Currents

Current meters were deployed from 15 March through 27 June 1996. Six current meters were deployed comprised of three electromagnetic current meters manufactured by InterOcean Systems (model S4), and three Acoustic Doppler Current Profilers (ADCPs) manufactured by RD Instruments. At the Main Basin reference site (Mooring 25; see Figure 5 for location) five Aanderaa (model RCM4) current meters were tethered from a submerged buoy.

Water profiles

Profiles of temperature, salinity, density and dissolved oxygen versus depth were obtained at 20 sites using a Seabird CTD on 18 March, 29 March, 18 April, 6 May, 20 May, 4 June, and 18 June 1996. Conductivity-temperature-depth (CTD) data from monthly monitoring by King County Department of Natural Resources at stations KSBP01 (located off Point Jefferson) and LSNT01 (located at the northern end of East Passage) were used to compute annual average temperatures for 1985–1996 (Table 1).

Drift cards

Because Duwamish River water is concentrated in the shallowest 8 m of the Bay where it is not cost-effective to deploy current meters, and information was desired regarding floating effluent materials, drift cards were released. Wooden drift cards bob in the upper few inches nearest the sea surface, where oil and grease effluent materials tend to reside (Word et al., 1990). Made of wood and coated with non-toxic paint, the cards were fabricated so as to pose minimal environmental harm. On each CTD cruise, batches of 50 individually numbered cards were released at eight of the CTD sites totaling 2,800 cards (see Figure 2 for locations). This paper describes 1,324 recoveries reported as of 12 July 1996 (47.3% of 2,800 total releases). Stringent project reporting requirements dictated the quick termination date.

Current Patterns in Density Strata

The CTD profiles indicated water strata defined by density gradients (Figure 3). Within the shallowest two density strata net current speed and direction were composited to ascertain the general current patterns. The paucity of records prevented an interpretation of the lower layer current patterns.

The records were combined regardless of season on the hypothesis that the dominant mechanism forcing the Bay above 50 m is the tidally pumped water exiting Colvos Passage (Figure 1; Ebbesmeyer and Barnes, 1980). The monthly average discharge from Colvos Passage tends to be relatively steady over the year (Ebbesmeyer et al., 1984).

Regarding the climate regimes, the first and third deployments at Mooring 25 exhibited current profiles characteristic of WD years, whereas the second deployment was characteristic of CW years (Figure 4). Averaged over the three deployments, the profile resembles that from the WD regime. Furthermore, the annual average temperature at 150 m fell in the range associated with the WD regime (Table 1). Since the most recent WD regime embraces the available current meter records, all of the records shown in Table 2 were utilized in the following interpretations.

Upper Layer (0– ~8 m)

The shallowest layer extends over the depth range of strongest vertical density gradients, or the sea surface to ~8 m. Few instruments have been deployed in this stratum because ship keels often penetrate deep enough to snag moored current meters. This layer is comprised of fresh water from the Duwamish River diluted with Puget Sound water. Because Duwamish River discharge is a small fraction of Puget Sound's total runoff (~1,200 m^3/sec), the shallowest layer is a relatively thin and

narrow ribbon of murky water snaking northward along Seattle's waterfront.

Forty current meter records obtained a meter above the sea floor along Seattle's waterfront showed a net convergence centered on the ferry terminal at Pier 52. Ferries idle there for about nine hours per day, generating an average westward discharge equalling 60–75 m^3/sec (Washington State Department of Ecology, 1995; Michelsen et al., 1998). The ferry-induced transport appears sufficient to interrupt the upper-layer flow headed north along Seattle's waterfront.

Intermediate Layer (~8–50 m)

Beneath the Duwamish River plume the intermediate layer consists of water formed by tidal pumping at The Narrows and ejected from Colvos Passage (Figures 1 and 5). Tidal currents flowing around Alki Point form residual eddies north and south of Alki Point (Figure 5). As the northern eddy spins it feeds a portion of the Colvos Passage water into inner Elliott Bay. The intermediate layer, as reflected by the density profiles, extends to the depth of no-net-motion as observed at Mooring 25 (50–80 m; Figure 4).

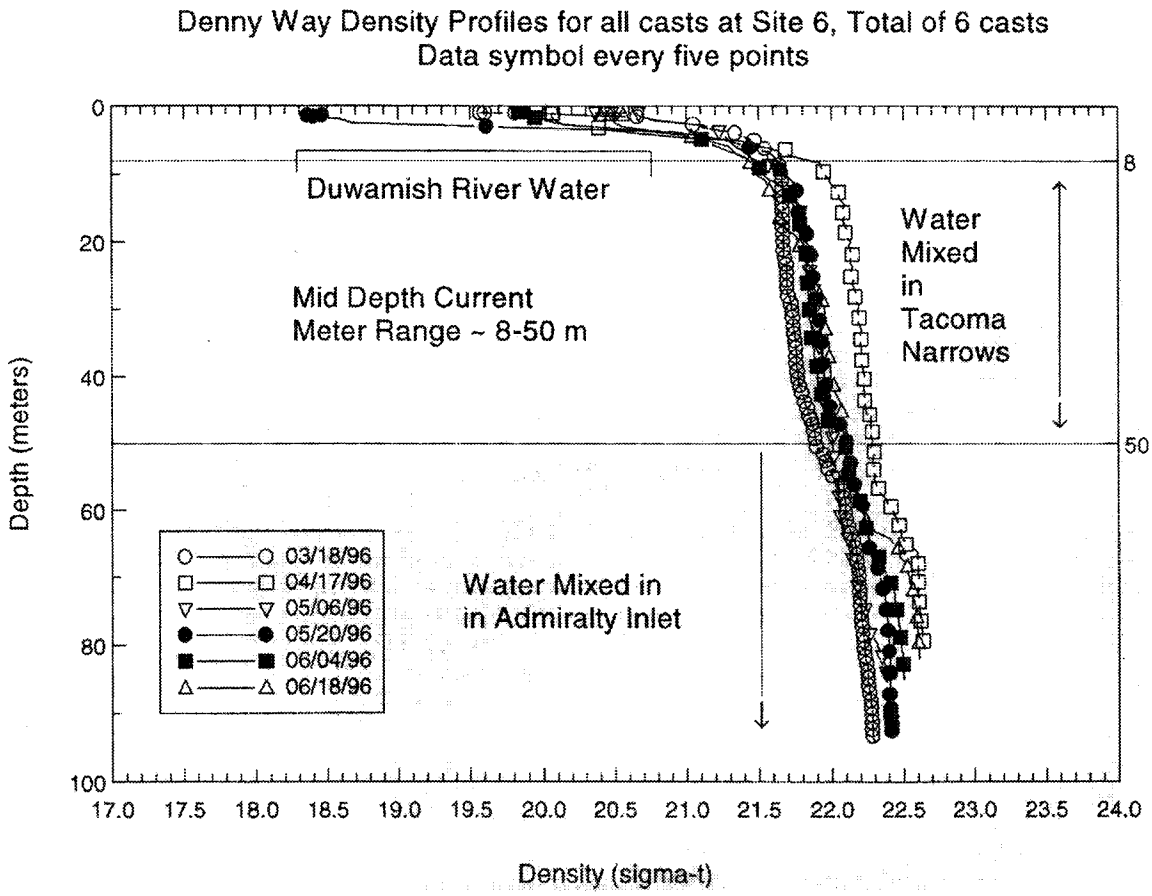

Fig. 3. Flow layers in Elliott Bay derived from density profiles. Six CTD casts made at Site 6 during the drift card releases are shown (see Figure 2 for site location; dates of profiles are shown at lower left). Symbols indicate every fifth data point obtained from the CTD profiles. The near-surface layer, characterized by strong vertical density gradients, contains the discharge from the Duwamish River. The mid-depth range contains water formed at the Tacoma Narrows, whereas water in the deepest layer was formed in Admiralty Inlet.

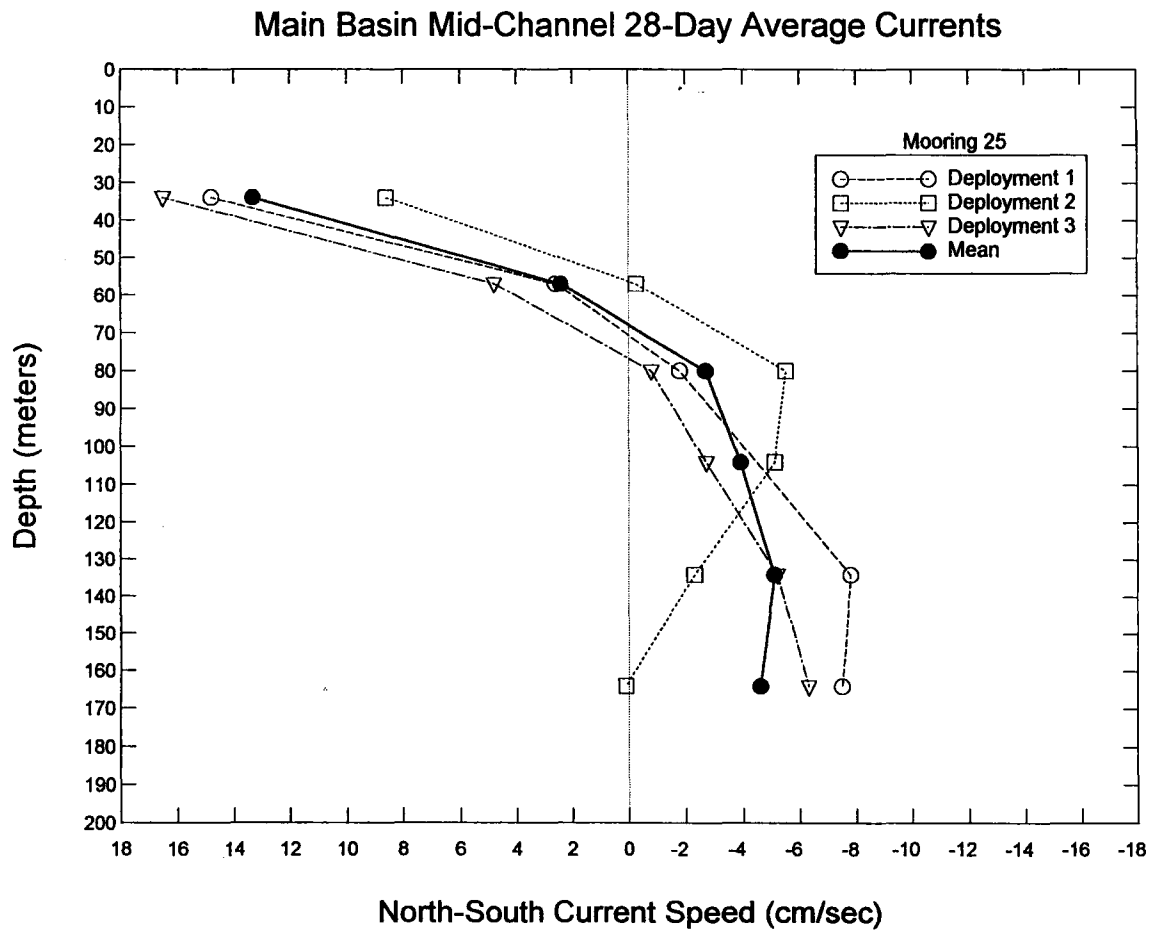

Fig. 4. Profiles of net north-south current speed in the Main Basin at Mooring 25. See Figure 5 for Mooring 25 location. Note that currents head north on the left and south on the right. Net speeds were computed from three, month-long current meter deployments (see code at upper right): deployment 1, 19 March–15 April; deployment 2, 20 April–17 May; and deployment 3, 25 May–21 June. The average of the three deployments is shown by the solid circles. Note that the depth of no-net-motion, corresponding to zero net current speed, varies between 55–75 m with a three-month average equaling 68 meters.

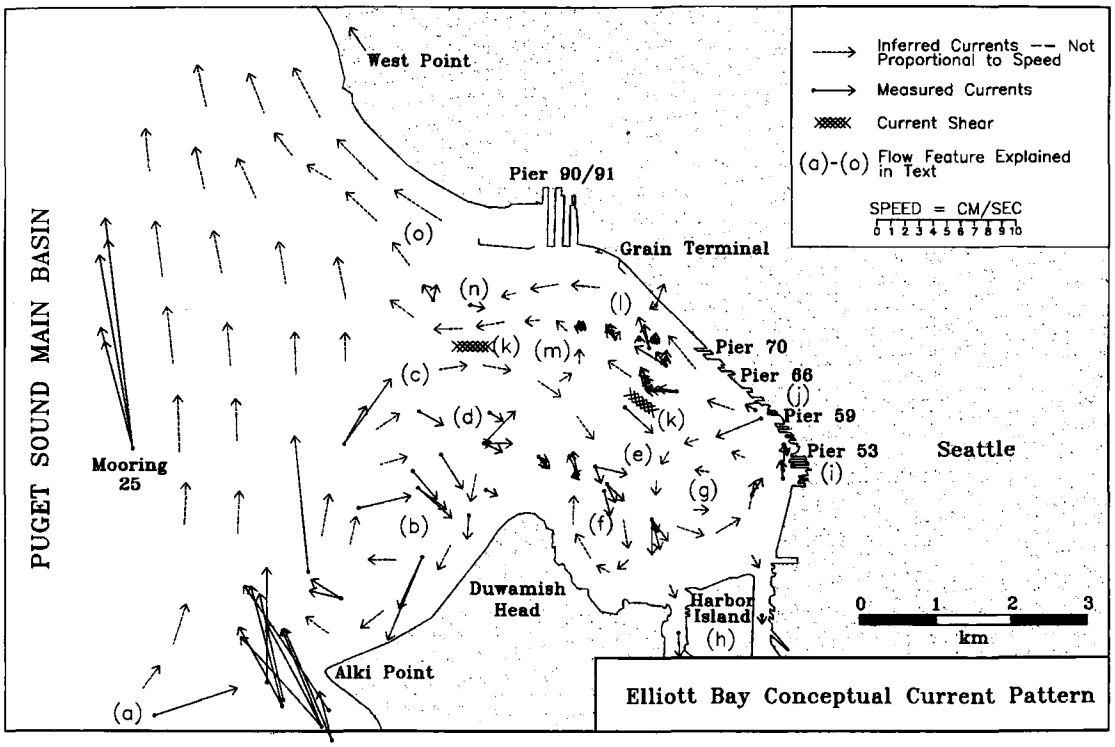

Fig. 5. Conceptual flow pattern, upper 50 meters, Elliott Bay. See text for explanation of codes a–o and box at upper right for codes of the current vectors. The current flow pattern shown in the Seattle Post-Intelligencer published on 23 April 1997 (Thursday morning edition; George, 1997) was adapted from this illustration. See Figure 1 for the broader context of this circulation pattern.

Combined Layers (0–50 m)

The elements comprising the Bay's flow pattern are (*a–o* shown in Figure 5; see also Figure 1):

a. Colvos Passage. At the northern end of Colvos Passage, half the flow diverges southward into East Passage, and half continues northward to Admiralty Inlet with a small fraction feeding into Elliott Bay. The refluxing model of Puget Sound indicates a net volume transport equaling 14,000 m^3/sec flowing past West Point (Cokelet, et al., 1991), and the hydrodynamic model of Liou (1991) suggests that 1,000 m^3/sec of the Colvos Passage efflux passes though Elliott Bay (i.e., ~4% of the Colvos Passage discharge).

b, c, d. Eddy North of Alki Point. During ebb tides, as water at mid-channel travels northward, an eddy develops in the lee of Alki Point. Because this eddy develops twice daily during major ebb tides, it influences currents averaged over long periods of time. Some of the water circulating in the Alki eddy diverges northward at *(c)*, and a portion spins around Duwamish Head into inner Elliott Bay at *(d)*.

e, f, g. Eddies of Inner Bay. Water diverging from the Alki Point eddy at *(d)* initially flows into Elliott Bay through the submarine canyon. As the water exits the canyon and enters inner Elliott Bay, the expanding flow may generate eddies, one to the north at (*m*) and the second in the southern portion of inner Elliott Bay. This flow may divide at (*e*) into eddies centered over the submarine canyons at *(f)* and *(g)*.

h. Inflow to the Duwamish River. At the southern terminus of inner Elliott Bay, small amounts of marine water are drawn southward into the estuarine flows within the waterways west and east of Harbor Island. Current measurements made approximately one meter above bottom indicate net southward speeds of approximately 1 cm/sec in the waterways (Kurrus and Ebbesmeyer, 1995).

i, j. Flow Along Seattle's Waterfront. A northward flow occurs along the Seattle waterfront, with two exceptions: the discharge from idling ferries may also influence flow in the intermediate as well as the upper layer; and near (j) the large net current directed westward may result from an anomaly in the seafloor bathymetry.

k, l, m, n. Flow Exiting Inner Bay. North of the submarine canyon the flow is directed westward. The hatched areas at *(k)* indicate currents separating the juxtaposed inflowing and outflowing waters. A portion of the inflowing water recirculates into the outflow at *(m)*. At *(n)* the outflow generally follows the bottom contours.

o. Outer Bay Flow. Water in the shallowest two layers exiting outer Elliott Bay merges with the Main Basin's upper layer.

Drift Cards

To quantify the drift card recoveries, the Bay's shoreline was segmented into 67 0.25-mile-long intervals (Figure 2). Nearly all of the cards recovered were found downstream (segments northwest of the drops) of the release sites, compared with a few percent in the upstream (segments southeast of the drops).

The fraction of drift cards recovered within the inner Bay was tabulated as a function of distance they were released offshore (Figure 6). Along the north transect, the recoveries decrease three-fold within 1,300 feet from shore. Between 1,300–3,800 ft offshore, the recoveries decrease from 30% to 15%. Of the 75% change that occurred within 3,800 ft, three-quarters occurred within the first 1,300 ft. Along the south transect, the percentage recoveries decreased after first increasing. The offshore maximum remains unexplained.

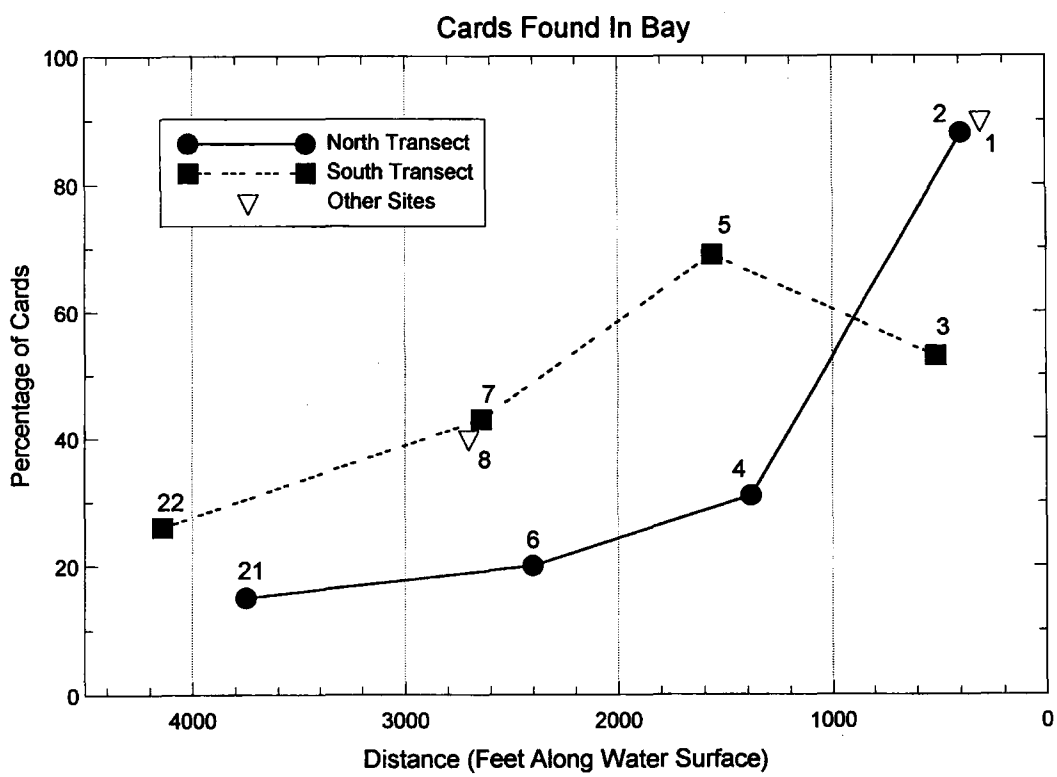

Fig. 6. Drift card recovery in Elliott Bay versus release distance from shore. Drift cards recovered within inner Elliott Bay versus the distance from shore where they were released along the north and south transects (see Figure 2 for transect locations). Zero distance corresponds to Mean Lower Low Water, and numbers indicate the drift card release locations shown in Figure 2.

Historical oceanographic observations indicate that along a given shoreline, floatable debris collects in localized segments. Realizing this, on a single occasion, investigators walked the shoreline from Alki to West Points searching for drift cards. Four shoreline segments accounted for 82% of the recoveries in the vicinity of the following facilities: Denny Way CSO, the pocket beach in Myrtle Edwards Park, the net pen fish farm in the vicinity of the grain terminal, and the Elliott Bay Park and fishing pier. All totaled, 93.4% of the cards recovered in Elliott Bay were found in 15 of the 67 segments. In other words, nine-tenths of the cards were recovered in one-fifth of the shoreline.

The 1,324 recoveries were tabulated in 16 regions of Puget Sound and Juan de Fuca Strait (Table 3; Figure 7). Overall, the recoveries reflect prevailing surface current patterns. Half occurred in inner Elliott Bay (Region 10) because of the proximity of the sites to the Bay's shore (Table 3). The next highest percentage (17.4% in Region 7) occurred between West Point and Admiralty Inlet because the cards tend to follow the near-shore currents exiting Elliott Bay around West Point. A few cards (3.8%) traveled south in East Passage. The cards that traveled beyond Admiralty Inlet were recovered on well-known collection shores of eastern Juan de Fuca Strait, including Dungeness Spit, Washington, and near Victoria, British Columbia.

Table 3. Drift cards released in Elliott Bay and reported in Puget Sound, and Juan De Fuca Strait. The numbers of cards recovered and the associated percentages of the total reports (1,324) are tabulated. All totaled 2,800 cards were released during three months (18 March–18 June 1996) of which 47.3% were reported by 12 July 1996. For maps of the drift card release sites and the recoveries superposed on the recovery regions, see Figures 2 and 7, respectively.

		Drift cards reported	
Recovery region (Fig. 7)	**General location**	**No.**	**%**
1	Pacific Coast	0	0
2	Western Juan de Fuca Strait	2	0.15
3	Eastern Juan de Fuca Strait	36	2.72
4	Georgia Strait	0	0
5	Admiralty Inlet	63	4.76
6	Whidbey Basin	29	2.19
7	West Point to Admiralty Inlet	230	17.37
8	Due west of Outer Elliott Bay	105	7.93
9	Outer Elliott Bay	70	5.29
10	Inner Elliott Bay	670	50.60
11	Exit area from Colvos Passage	51	3.85
12	East Passage	50	3.78
13	Colvos Passage	1	0.08
14	Southern Puget Sound	0	0
15	Rich Passage	17	1.28
16	Hood Canal	0	0
Total reported		1,324	100.00%

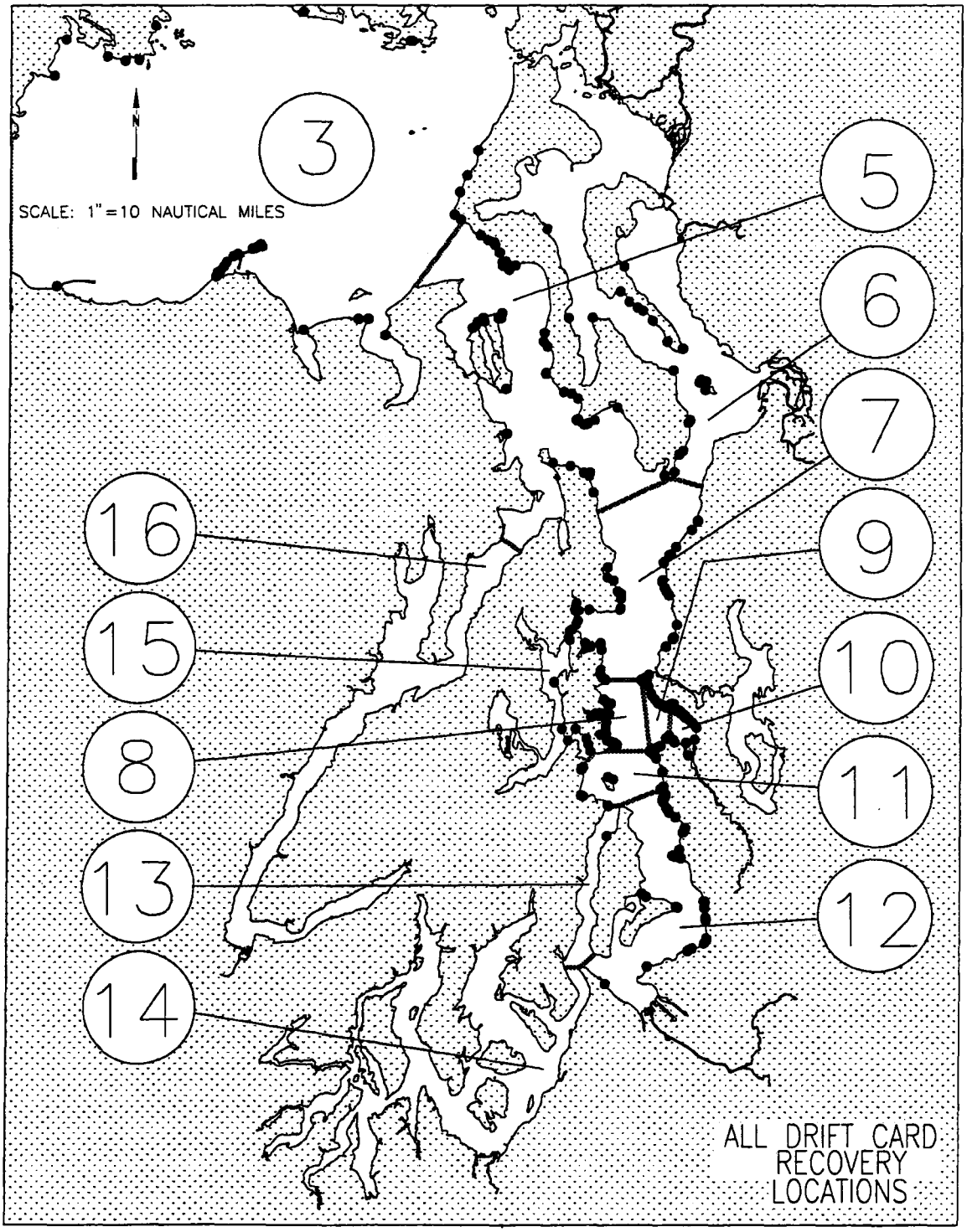

Fig. 7. Recoveries of Elliott Bay drift cards in Puget Sound and Juan de Fuca Strait. Region 1 includes the Pacific coast and region 2 is the western Juan de Fuca Strait adjoining region 3. See Table 3 for tallies of cards found within each division.

Discussion

Despite the accumulation of 229 current meter records at a cost exceeding $1 million, Elliott Bay's flow field remains unresolved to a substantial degree, particularly in the layers shallower than 8 m and deeper than 50 m. The southern portion of inner Elliott Bay may contain an eddy pair, which may be a significant factor in determining the flushing of inner Elliott Bay.

The available historical data suggest a persistent circulation through inner and outer Elliott Bay. What drives the persistent flow? We believe it originates in Colvos Passage because of tidal pumping at The Narrows. Water drawn from East Passage into The Narrows on a flood tide is, with an admixture of Southern Puget Sound water, expelled on the following ebb into Colvos Passage. Monthly averages of the tidally pumped discharge in Colvos Passage shows that it fluctuates less than approximately 10% through the year (Ebbesmeyer et al., 1984). Of the approximately 28,000 m^3/sec discharge exiting Colvos Passage, approximately half continues northward mostly bypassing Elliott Bay, and half refluxes south into East Passage (Figure 1). The present synthesis suggests that a small portion of the Colvos Passage discharge persistently circulates through Elliott Bay.

Within 24 days after the last drift card was released (18 June 1996) the public had reported 47.3% of the total deployed (2,800). The only other sizeable release of drifters in Puget Sound was recently made in Southern Puget Sound involving 9,950 cards deployed inland of Dana Passage during October 1996–September 1997 (Ebbesmeyer, et al., 1998). Within five months the public reported 51.3% of those releases.

The foregoing percentages suggest that there is about a 50% chance of the public reporting a marked drifter floating in the main stem of Puget Sound south of Admiralty Inlet. North of Admiralty Inlet in Juan de Fuca Strait, the percentage recovery decreases by half, based on three previous compilations: 26% of 20,000 historical drifters released throughout Juan de Fuca Strait (Ebbesmeyer et al., 1995); 21.3% of 13,800 drift cards released along the Strait's central axis during January–March 1992 (Ebbesmeyer et al, 1995); and 24.1% of 1,000 cards released off Victoria during June–July 1997 (Crone et al., 1998).

The two-fold difference in recovery percentage between the Sound and the Strait stems in part from the greater numbers lost to the Pacific Ocean from Juan de Fuca Strait than from Puget Sound. The lower population density in the Strait may be contributing factor. Nevertheless, a large fraction of marked floating drifters wash up within the proximity of the public walking the shores of Puget Sound.

Acknowledgements

This investigation was funded by the King County Department of Natural Resources under a subcontract from Brown and Caldwell, Inc. to Evans-Hamilton, Inc. as part of the Denny Way/Lake Union CSO Control Project. We thank Kevin Schock for assistance with the King County current meter records. We thank members of the public who reported drift cards.

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Intensive Field Sampling Program in Support of a Numerical Toxicant Fate and Transport Model and Risk Assessment: Elliott Bay and Duwamish River, Washington

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Scott Mickelson
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Abstract

A field sampling program was undertaken in the winter of 1996–97 to provide the data to support a hydrodynamic and toxicant model and risk assessment on CSO discharges in the Elliott Bay/Duwamish system. This effort sampled conventional parameters, bacteria, trace metals, and organic compounds in matrices including the water column, sediments, CSO discharges, and fish and invertebrate tissues. Water column and sediment samples were taken weekly, with daily water samples taken for the three days following CSO events. CSO samples were taken by automated samplers. Biological samples were obtained through a number of methods, including fishing and trawling.

The hydrodynamic portion of the model was developed through the use of current meters and automated water level, temperature, and salinity recorders.

Numerous specialized sampling and analytical techniques were used. Organic concentrations were too low to detect using our traditional sampling and laboratory methods. Semi-permeable membrane devices were deployed to assess water column concentrations of organic compounds, these samplers estimate the average concentration of organic compounds over time. Low level mercury sampling was also employed to estimate mercury concentrations in the water column.

Sample results are presented in terms of depth, location in the estuary, date, and storm events.

4B: Urban Influences on Water Quality: Elliott Bay/Duwamish Estuary Monitoring and Assessment

Questions & Answers

Q: Kevin, I was a bit surprised that some of the metals data in Elliott Bay didn't have much of a tidal component to it, although the chromium values looked like they had some variability and I wondered if that was at all tidal – as that interface between the fresh and salt water works its way back and forth. They were relatively constant except the chromium did look like it was a little bit variable. Is that possibly tidal?

A: I haven't done any sort of spectral analysis on that to determine if there is a tidal component. We did regress the data against flow in the Green River. I think we also regressed it against rainfall events. I don't think I regressed it against any tidal components, but if you plot up the cadmium, there really isn't that much variance. We didn't do chromium.

Q: There was one slide that , the very beginning, kind of showed a variation.

A: The arsenic and the cadmium were kind of the same. There wasn't much variance in the data itself to indicate that there was some sort of tidal component in that, but I did not do a regression to check that specifically.

Q: In the PSAMP database, there's a reasonably high level of mercury in the sediments in Sinclair Inlet over near Bremerton. They attribute a lot of that mercury, or mercury inputs presently, in the wastewater treatment plant flow from Bremerton and Kitsap number five. And that's sort of, I guess, attributed to switches or some mercury-based products that somehow end up in the wastewater stream and that was a bit surprising to me and I just wondered if anyone could comment on what mercury values in the discharge either from the wastewater treatments plants or from the CSO's might be and in light of Curt's discussion on prop wash, what other possible explanations there might be for the high mercury values in the PSAMP database.

A: The average is about 54 nanograms per liter, but that's based on two samples. We had to use ultra clean sampling methods before we could even measure it in the CSO's, so you had one that was maybe about 30 and then another one that's 65, or something like that. It averaged out to around 54 nanograms per liter. That was one CSO.

Q: Chuck Boatman, Aura Nova Consultants. I think this is for Kevin. You mentioned that the partitioning coefficients for the metals were constant throughout the estuary in the model, but they were based on field data. Can you explain how you derived those?

A: Yes we used total and dissolved and then total suspended solid concentrations. A fairly simple calculation to get back at the partitioning coefficient. There was no extensive laboratory analysis where you actually measure the amount of chemical that was absorbed to the suspended solids.

Q: And a related question. The calibrations for metals you showed, I assume those were all, was that total metals or suspended solids?

A: That was total.

Q: Did you do calibration for the dissolved metals?

A: No, we did not.

Q: Hi, Roseanne Lorenzana with EPA here in Region 10. I have a question for almost all the speakers. I don't know how much time we have, so stop me when we need to go. For Kevin, I had a question abut the model. You described a decay component and on your slide it just said lumped. And I wasn't quite sure what you meant by that. Is this decay component just for transport or is it for biotic as well as abiotic decay?

A: It includes everything from proteolysis to hydrolysis, whatever sort of decay component that you can have for any particular constituent.

Q: And what does "lumped" mean?

A: These many processes are going on and basically you lump all those decay processes into one value.

Q: In your simulation, that was really nice computer simulation and I've never seen anything like that before, so I'm not sure what I was seeing. Was there an upstream flow component to that?

A: Yes there was. There was a freshwater flow input from the Green River coming into that, and that's what caused most of that surface layer to go downstream at a more rapid rate.

Q: But there was always an upstream, I mean it went backwards.

A: Well that was tidal forcing. You actually get reverse flow conditions.

Q: Can that information be used to verify that some of the reference sites that John talked about are not impacted by the CSO's?

A: Well, we are using the mussel data within the model calibration as well. So the model simulates transport within the system.

Q: Randy, on the semi-permeable membrane device for organics, was that measuring total or dissolved or both?

A: I'd say it's a combination of both because if you have a particle actually hitting the device there'll be some partitioning going on.

Q: Are you able to distinguish total from dissolved?

A: No. If you really want more detail on that, I would talk to Eric Crecelius about that. We should get out of here pretty soon.

Q: Curtis, your drift study shows what's happening on the surface at Denny Way. What is happening at the bottom on Denny Way, and what would happen after regime shift?

A: The drift cards probably reflect down to ten meters depth. I don't know where the Denny Way outfall is going to be built, so I don't know how deep it's going to be. The regime shift, we think, should occur in the next few years, and we don't know what the circulation will be in Elliott Bay. It might be quite different, so unfortunately regimes last 20 years, about the length of most of our careers. So another generation might come up and do the next one, so stay tuned for 20 years.

PUGET SOUND RESEARCH '98

SESSION 4C

ABUNDANCE AND DISTRIBUTION OF FISH AND MACROINVERTEBRATES

Session Chair:
Sandra O'Neill
Washington State Department of Fish and Wildlife

Olympia Oyster Stock Rebuilding Plan for Washington State

Anita E. Cook and J. Anne Shaffer
Washington Department of Fish and Wildlife, Point Whitney Shellfish Lab

Brett Dumbauld
Washington Department of Fish and Wildlife, Willapa Field Laboratory

Background and Introduction

The Olympia oyster (*Ostrea lurida*) is native to the Pacific coast of North America and occurs in marine waters from Bahia de San Quentin, Baja California, to Sitka, Alaska (Ricketts and Calvin, 1968). It primarily inhabits sheltered waters or estuaries. Once common in Washington State, the Olympia oyster now has a restricted and very patchy distribution in Willapa Bay, Grays Harbor, and southern Puget Sound.

The Olympia oyster has been the focus of human harvest for several thousand years. The oyster has an important identity for the Washington tribes who used the oyster, named Tusa'yad by the Skokomish, extensively, and often based settlement locations on its harvest (Washington Secretary of State, 1935; Elmendorf, 1992; Steele, 1957). With European colonization, the Olympia oyster supported a large commercial industry. Olympia oyster beds from Puget Sound, Hood Canal, and Willapa were harvested extensively, and later cultivated with an elaborate system of dikes (Steele, 1957; Westley et al., 1985; Brown, 1976). Overharvesting in the late 1800s and severe water quality problems in the 1930s to 1950s caused Olympia oyster stocks to crash, and the industry to terminate.

Recent interest and concerns about the status of native Olympia oyster stocks in Washington State waters, widely recognized to be reduced from historical levels, led the Washington Department of Fish and Wildlife (WDFW) to begin developing a stock-rebuilding plan. General goals of Olympia oyster stock rebuilding include wise stewardship, maintenance of genetic integrity, and ecosystem restoration. The goal of the Olympia Oyster Stock Rebuilding Plan is to restore and maintain Olympia oyster populations on public tidelands in their former range.

Status of the Population

Current and historical distribution of Olympia oyster in Washington coastal and inland waters is summarized in Figure 1.

Historical Population Size and Distribution

Olympia oyster stocks were historically very large in Washington State with reported annual landings of over 130,000 bushels around 1890, principally from Willapa Bay. Within the inland waters of Washington, the Olympia oyster had a scattered distribution throughout Puget Sound and Hood Canal (Westley, 1976). Samish Bay once supported a large, naturally occurring Olympia oyster population, which was severely depleted in the 1800s by overharvest (Brown, 1976). The most abundant natural Puget Sound populations historically occurred around Olympia, primarily in Mud and Oyster Bays (Steele, 1957).

Current Population Size and Distribution

The oyster is present on oyster reserves in North Bay, Case Inlet, and southern Puget Sound, where dense natural sets have been observed in the years 1995–1997. Shellfish growers in south Puget Sound noticed similar sets in the mid-1980s, but these were subsequently wiped out by severe

winter weather. Comparison of historical documents and local knowledge indicates that current numbers are at best a mere fraction of, and possibly more ephemeral than, historic populations.

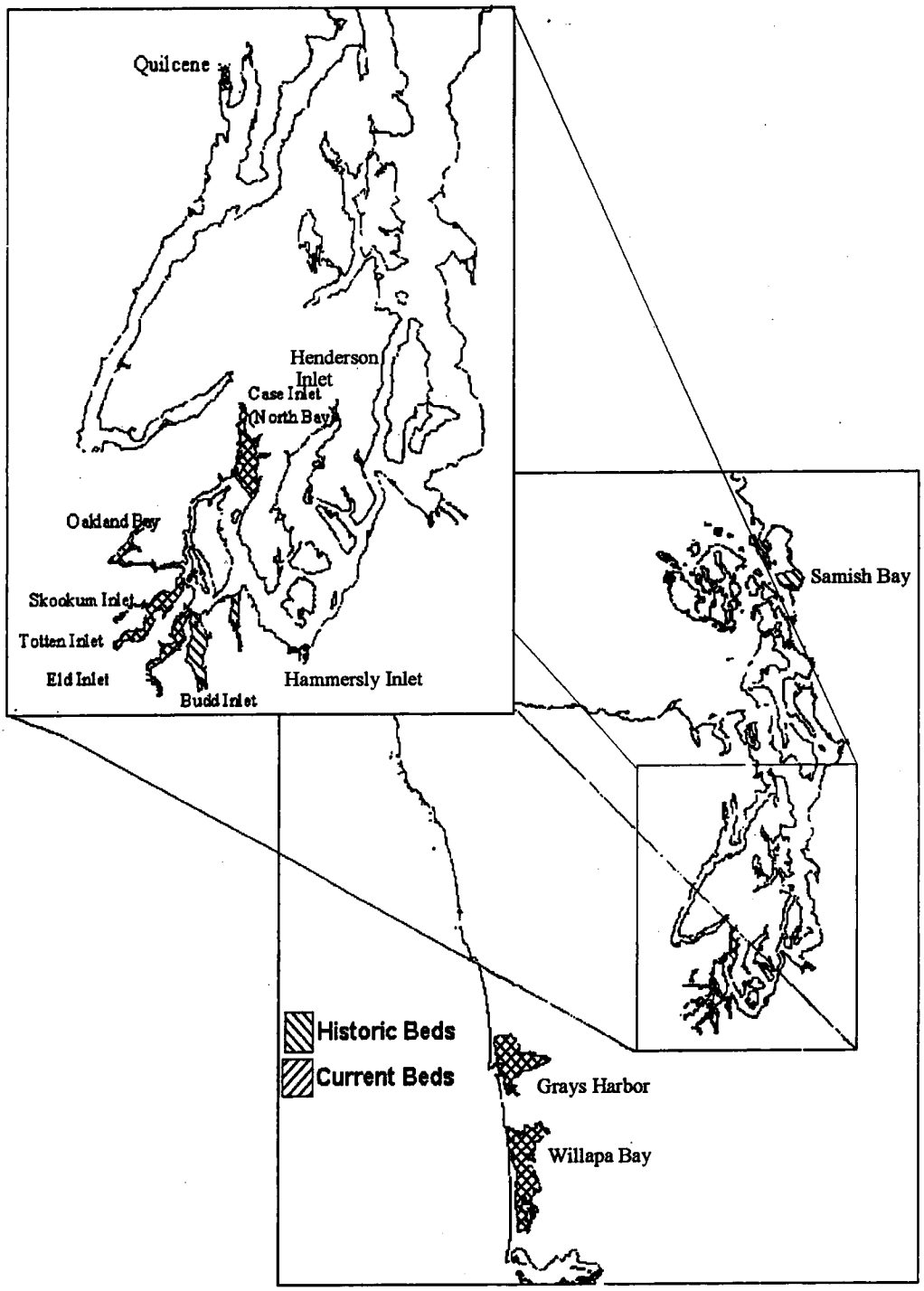

Figure 1. Current and historic distribution of the Olympia oyster in Washington State.

Management

Olympia oysters will be co-managed with the tribes and other government agencies, according to the provisions in the federal district court's orders and judgments filed in United States v. Washington No. 9213, subproceeding 89-3. The following is a synopsis of current management.

Non-Tribal Fishery Management

Non-Tribal Commercial Fishery: WDFW harvest reports from 1897–1990 (Figure 2) show a general decline in commercial production of Olympia oyster from a high of >200,000 gallons in the early part of the century to an annual production of <1,000 gallons since 1979. Preliminary data for the years 1991–1996 show an annual commercial harvest of approximately 500 gallons (about 4,000 pounds of shucked oysters), mostly occurring in south Puget Sound on private tidelands.

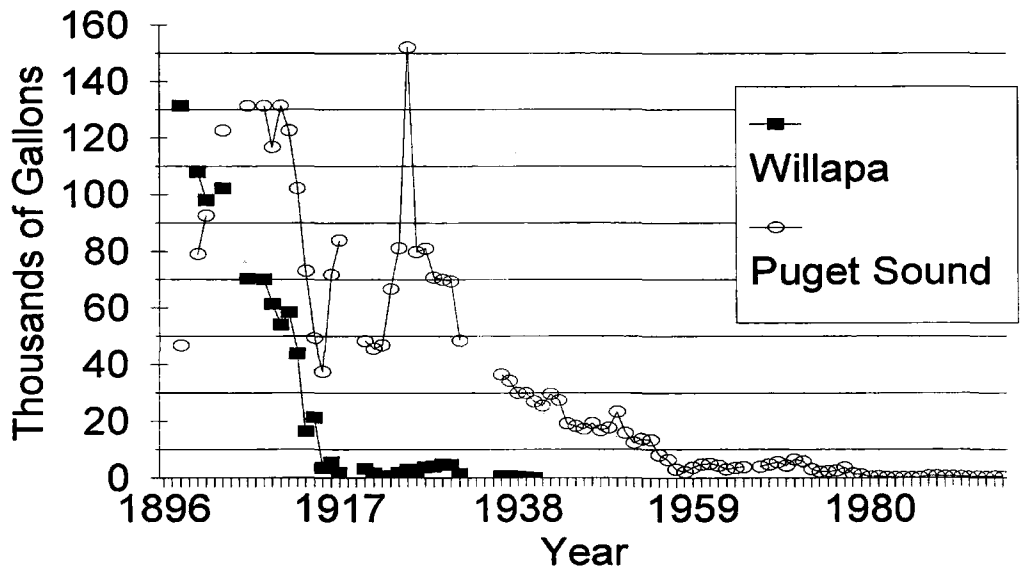

Figure 2. Olympia oyster production in Washington State.

There are currently three commercial Olympia oyster growers that operate solely on private tidelands on Puget Sound. Management of stocks on private tidelands is controlled by private growers. Washington State Department of Health requirements must be met, and quarterly harvest reports are required by WDFW.

Oyster reserves were established in 1890 for the preservation and growth of Olympia oysters (Woelke, 1969). The reserves originally consisted of 11,239 acres in Willapa Bay and 4,500 acres in Puget Sound. Some lands have since been sold by the legislature. Reserves currently encompass 10,000 acres in Willapa Bay and 1,000 acres in southern Puget Sound.

With the decline in the Olympia oyster population, reserve laws were changed in 1947 to reflect the growing importance of the Pacific oyster, *Crassostrea gigas*, on reserve tidelands, particularly in Willapa Bay. Willapa Bay reserves are now actively managed for commercial harvest of the Pacific oyster. An average of 54,000 bushels of Pacific oysters are sold each year from managed intertidal tracts and $79,000 returned annually to the state general fund (Dumbauld and Kauffman, 1996). Growers are required to return 40% of the live oyster volume in shell to the tracts to maintain stocks via natural spawning and settlement.

No commercial oyster harvest occurs on the public lands of Puget Sound oyster reserves. While Olympia oysters exist on both the Willapa Bay and Puget Sound reserves, no active management has

occurred for this species and the last commercial harvest of Olympia oysters on reserve tidelands in Puget Sound took place in 1929.

Non-Tribal Recreational Fishery: The Olympia oyster has been managed passively on public beaches for many years. Olympia oysters are included in the regulations that apply to all classified oysters. Current harvest limits include: 1) combined daily limit of 18, and 2) oysters must be shucked on the beach and the shells left at the same place/tide height where they were taken. They may be harvested only by hand or with a hand-held manually operated prying tool (no hammers, etc.).

Beginning 1 May 1998, new regulations will be in place for all areas except Hood Canal (e.g., south of Foulweather Bluff) and the outer coast. These regulations will include size restrictions designed to minimize recreational harvesting of Olympia oyster.

All oyster reserves are currently closed to intertidal recreational clam and oyster harvest, with the following exceptions: 1) one Oakland Bay beach is open to clam harvest only; 2) a North Bay reserve beach, which is open to both clam and oyster harvest beginning in 1998; and 3) two areas on the Long Island Oyster Reserve have been opened for clam and oyster harvest. Seasons for non-reserve beaches are set based on the population and projected harvest of Pacific oysters. With the exception of one beach in North Bay, Puget Sound oyster reserves are not currently actively managed for oysters. Oyster dikes in Oakland Bay have created excellent habitat for Manila clams. Although the majority of these reserves are closed to recreational clam and oyster harvest due to access issues, these Manila beds provide stock to trade with the tribes to enhance other recreational opportunities.

Tribal Fishery Management

Tribal Commercial Fisheries: Tribes of inland and coastal Washington have played a dominant role in historic commercial harvest of Olympia oysters (Steele, 1957) and at least one tribal war was fought over rights to harvest Olympia oysters (Swan, 1857; Esveldt, 1948; Steele, 1957). There are no known current targeted tribal commercial fisheries for Olympia oysters. However, commercial harvest of Olympia oysters is not prohibited in the State/Tribe Interim Management Agreement except in areas the state has declared as artificial beds. The Point No Point Treaty Council Tribes are the only tribes that have issued regulations for commercial oyster harvest (species not specified) on public tidelands, and their annual commercial regulations have a clause prohibiting the harvest of oysters less than two inches in length during openings for single oysters, which would eliminate virtually all harvest of Olympia oysters. The majority of tribal oyster openings are for single oyster harvest. Some harvest of Olympia oysters could potentially occur when clusters are harvested, which has occurred recently at only a few beaches.

Tribal Ceremonial and Subsistence Fisheries: Olympia oysters may be harvested in ceremonial and subsistence fisheries.

Status of Genetic Integrity of Olympia Oyster Stocks

Conserving the natural genetic integrity of Olympia oyster stocks is an important component of any stock recovery strategy. Artificial enhancement of Olympia oyster stocks should meet acceptable standards for maintaining genetic stock integrity for indigenous species. Some standards to be met are: 1) brood stock for seed production should come from the same geographic area where seeding will take place; and 2) the minimum number of brood stock necessary to maintain genetic variability while maintaining stock identity should be established and maintained.

Research suggests that the rate of natural genetic exchange between coastal populations in Washington, Oregon, and northern California is low (Baker, 1995); however, no information exists on genetic exchange within Washington waters. This is particularly important when considering historic Olympia oyster farming practices, which included seed transport both within and between regions. Genetic integrity will be a topic for further dialog in Olympia oyster rebuilding efforts.

Factors Affecting the Population

Habitat and Water Quality

Pollution has been shown to be the number one factor in the demise of the Olympia oyster throughout lower Puget Sound and Hood Canal. Sulfite waste liquor (SWL) from the Rayonier pulp mill built on Oakland Bay in 1927 was identified as the reason for the demise of all south Puget Sound Olympia oyster stocks. Tidal currents carried effluent to Oakland Bay beds within a tidal cycle, and throughout lower Puget Sound within a matter of days. Dramatic population crashes, witnessed throughout the Olympia oyster beds, destroyed the industry by the mid-1940s. The Rayonier mill was closed in 1957. Unfortunately, the industry had crashed by that time, so monitoring of the Puget Sound and southern Hood Canal populations had ceased (Steele, 1957; Gunter and McKee, 1960).

Water quality impacts in Washington's waters have shifted over the last 40 years from industrial effluent to non-point source pollution. Impacts of contemporary water quality degradation to residual Olympia oyster stocks is not known. Contemporary water quality impacts to Olympia oysters of the coast and inland waters include: low dissolved oxygen (DO), chlorine from sewage outfalls, non-point pollution and associated eutrophication, sedimentation and siltation, and herbicides (Couch and Hassler, 1989; Dumbauld, 1997; McMillen, 1978).

Harvest

Overharvesting has been identified as the leading cause of Olympia oyster stock crashes in Samish Bay (Puget Sound) and Willapa Bay in the 1800s. Harvesting of other commercially valued species may also impact the Olympia oyster where they co-occur.

Interspecific Interactions

After the initial declines, additional factors continued to prevent Olympia oyster recovery. Introduced predators (the Japanese oyster drill *Ocenebra japonica*, the flatworm *Pseudostylochus ostreaophagus,* and the copepod *Mytilicola orientalis*) have resulted in poor oyster condition, and in the case of drills, have caused high moralities (Peters, 1993). Natural predators, including starfish and diving ducks, also are thought to suppress Olympia oyster recovery. Other disturbances, including substrate disruption by ghost shrimp and mud shrimp, smothering by slipper shells, and competition with Pacific oysters for space and setting habitat are thought to affect Olympia oyster recovery negatively (Dumbauld, pers. comm.; Westley, 1976; Brown, 1976; Steele, 1957).

Stock Rebuilding Actions

Restoration of this species may include both natural and artificial enhancement strategies. Natural restoration techniques, such as water quality and habitat improvements will be the primary focus. Based on this focus, there are a number of objectives and actions necessary to rebuild Olympia oyster stocks in Washington State. Priorities, which vary with region, include:

1. Working with local experts, including the tribes and shellfish growers to define the historic and current distribution of the Olympia oyster;
2. Conducting population surveys to define current population levels to establish a benchmark for long-term monitoring and management; and
3. Defining water quality and interspecies interactions at a regional level, and identifying priority areas for restoration based at least in part on these interactions.

Acknowledgments

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Intra-Annual Changes in the Abundance of Coho, Chinook, and Chum Salmon in Puget Sound in 1997

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Introduction

Three surveys were conducted in Puget Sound during the spring, summer, and fall of 1997 (Figure 1). Using a large rope trawl designed to fish in midwater, we were able to sample surface waters for juvenile salmon as well as fish throughout the water column. The use of large rope trawls to study the marine life history of Pacific salmon is new. The large net captures fish of all sizes when a small mesh liner is used in the cod end. The work reported here is the result of only three short cruises in one year, yet there are some surprising observations. The study identified several relationships that appear to provide new information about the early life history of juvenile salmon. We think that this new information is sufficiently important to management that we are reporting it now. We believe that a continuation of the work and the testing of a new theory on the natural regulation of salmon abundance (Beamish and Mahnken 1998) will provide explanations of the factors regulating the marine carrying capacity for chinook and coho in particular and Pacific salmon in general.

Methods

Rope Trawl

When fishing to design specifications the rope trawl has an opening 21 m deep and 64.5 m wide (Beamish and Folkes 1998). In Puget Sound, we did not follow a predetermined survey design, as this was the first survey. Most sets were at the surface but other depths (15 m, 30 m, 45 m, and ≥45 m) were fished in approximate proportion to the expected relative abundance of all species of Pacific salmon. The length of sets was related to the amount of fish that were expected to be captured. We found that 1/2-hour sets produced catches that could be processed in the interval between sets or throughout the day. We were also concerned that we did not catch too many juvenile salmon. We note that the juvenile salmon populations were in the process of undergoing substantial natural mortality and our samples would be equivalent to a very small percentage of this natural mortality. During each of the three cruises, between 12 and 23 fishing sets were made in the following locations: Admiralty Inlet, Puget Sound, Possession Sound, East Passage, and Colvos Passage. Crews worked 12 hours per day during daylight. We towed the net at approximately five knots, except for deeper tows, which were possible only at four knots.

The abundance estimates used in this report are primarily an index of catch per unit effort. We wanted to emphasize the relative abundances among species during the various cruises as a general indication of the numbers of individuals. We consider that the abundance estimates are both approximate and preliminary. However, we also consider them to be minimal estimates.

Abundance

Abundance estimates were made using the catch from the volume of water fished (swept volume). We assumed that all fish in front of the opening were captured. We doubt that this is true because unpublished Russian data indicate that for a net that fished 50 m x 50 m, only 1/3 of the juvenile Pacific salmon (but larger than ocean age-0) were captured (Shuntov et al. 1988, 1993). Thus we believe that our abundance estimates are minimal, but can be used as a relative index of abundance.

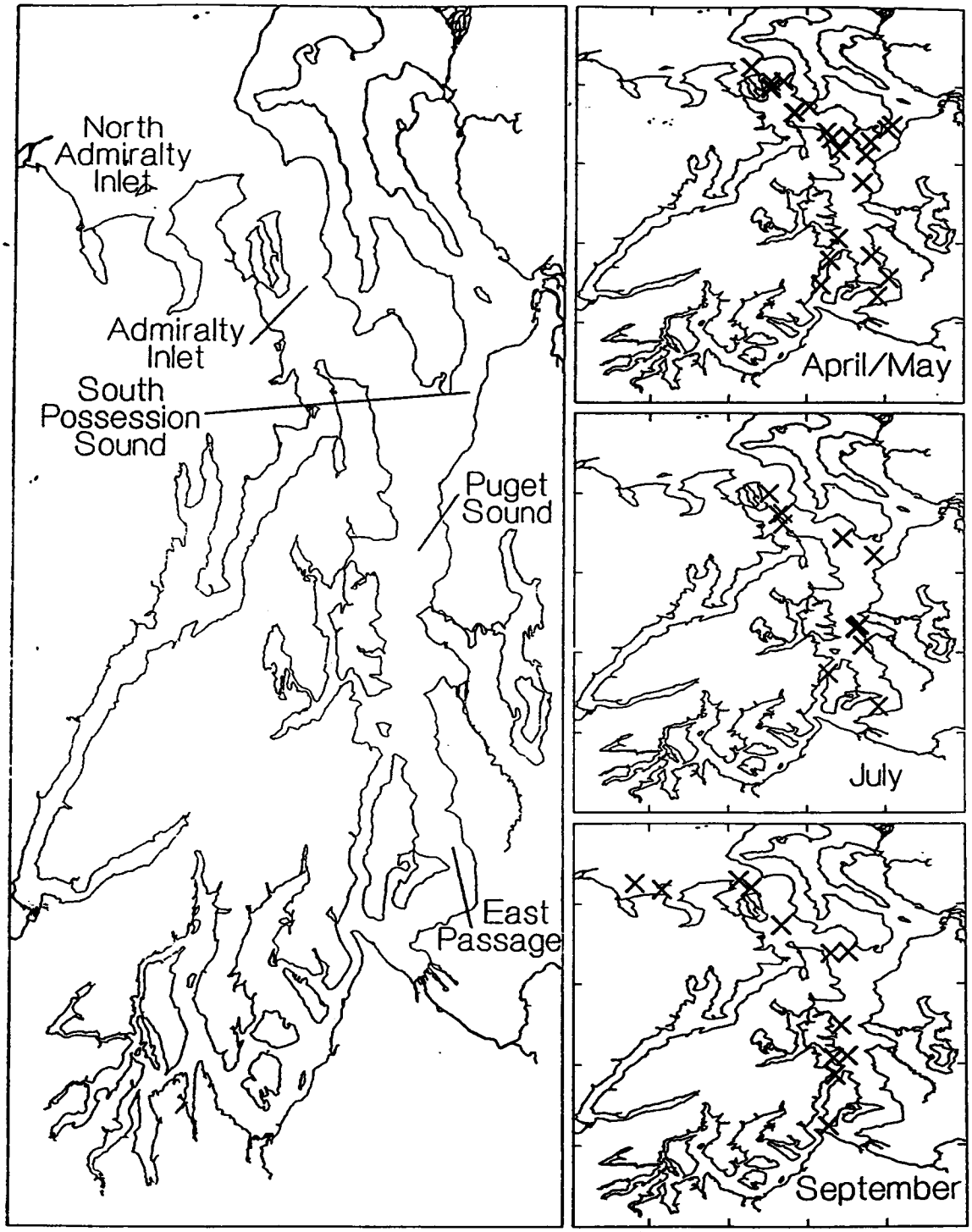

Figure 1. The five salmon management areas within Puget Sound that were surveyed (left figure), and the distribution of fishing sets (all depths shown) during each cruise (right figures). Each 'X' represents the location of one fishing set.

Abundance estimates were determined for ocean age-0 chinook, coho, and chum salmon. Only catches in the top 30 m were used, as almost all the catches were made within this depth (Figure 2). Catches with a headrope depth of 0–5 m were placed in the 0–15 m stratum, and those with a

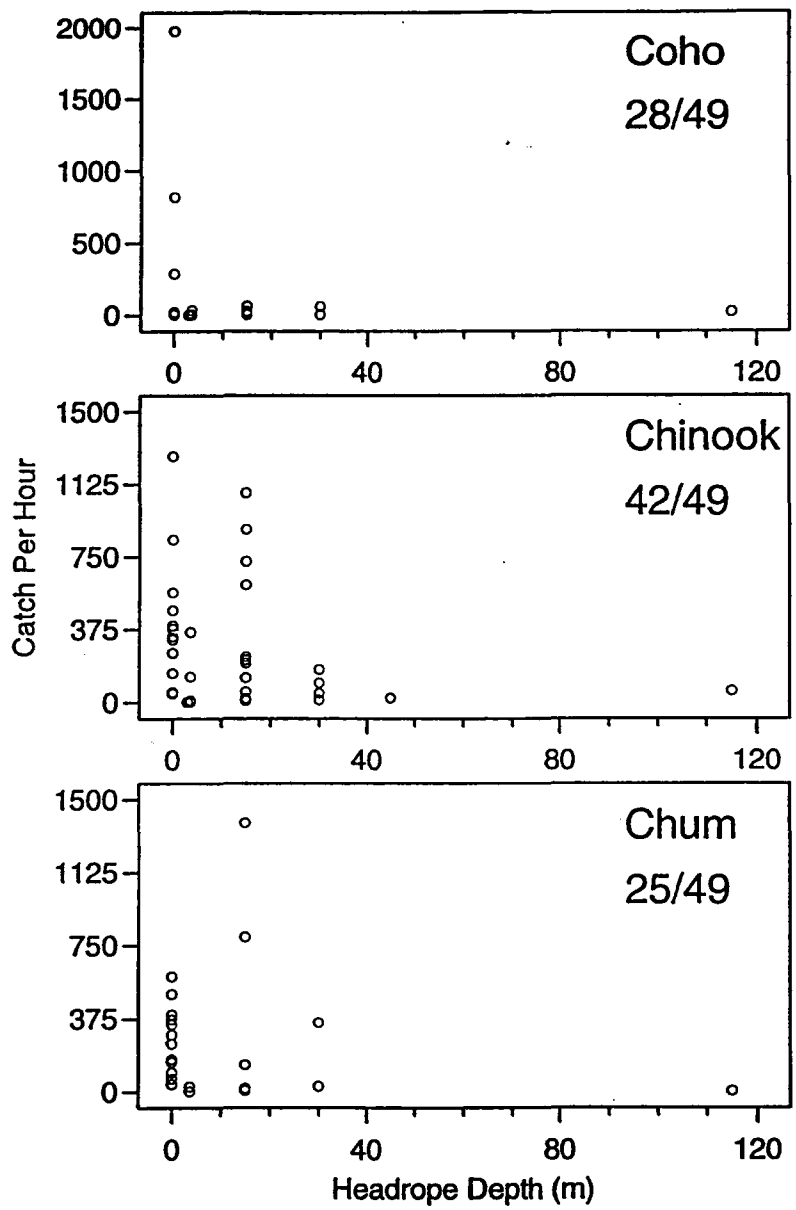

Figure 2. Catch per hour of juvenile coho, chinook, and chum salmon stratified by headrope depth. Zero catches are not shown; the ratio refers to the number of sets with catches of the species/the total number of sets.

headrope depth of 16–20 m in the 16–30 m stratum. There were no sets with headrope depths 6–15 m or 17–30 m. Abundance was estimated using the volume strained for each set, dividing the total volume of that stratum in Puget Sound by this volume and multiplying by the catch. The abundances estimated for each set were then averaged, and the estimates from the two strata were added together. The area of Puget Sound is 2330 km^2 (Thomson 1994). Confidence limits were determined for each estimate, but were so large (frequently ranging from a value of 0 to 2 or 3 times the estimate) that they have not been reported.

All salmon were examined for missing fins and coded wire tags (CWT), and most salmon were measured for fork length. Randomly selected samples were examined for stomach content and otoliths were removed.

The identification of juvenile salmon is not a trivial matter. Common criteria involving color and general appearance can cause problems. We used measurements, counts, and otolith shape to ensure that identifications were accurate. Chinook and coho were readily separated from pink, chum, and sockeye juveniles by the presence of spots on the body, the size and spacing of gill rakers, the number of branchiostegal rays, and otolith size. The chinook otolith is approximately two times larger than a coho otolith and is an excellent character for separating these species. Pink, chum, and sockeye were separated using gill raker number, length and spacing, scale size and number, and body markings. A useful character is the longer length of the intestine of chum salmon relative to pink and sockeye.

Results

Catches

In this report we summarize the catches of salmon (Pacific and Atlantic) and report the results of our studies of the three dominant species of Pacific salmon: coho (*Oncorhynchus kisutch*), chinook, (*O. tshawytscha*), and chum (*O. keta*). Catches of non-salmon species will be reported elsewhere. The set distances for each of the three cruises (Figure 1) were approximately 5.1 km. There were 49 sets completed in the three cruises, 49% in the 0–15 m depth interval, 31% in the 16–30 m interval, 8% in the 31–45 m interval, and 12% deeper than 45 m (Table 1). Chinook and chum were the most abundant salmon in the catches, followed by coho (Table 2). There were small catches of juvenile pink, sockeye, and steelhead, and of two Atlantic salmon that had escaped from net pens. We separated catches into juveniles with an ocean age of zero and those with an ocean age of one year (one winter annulus) or greater. In this report, lengths were used to partition fish into the two age groups. This method works well for all species except chinook in April/May and July. For chinook, for these cruises, we defined ocean age-0 fish as ≤100mm in April/May and ≤190mm in July. A sample of 91 selected fish was aged from the smallest length frequency distributions in April/May. Four of the 91 were stream type with an ocean age of zero. For this report, these fish were not included as ocean age-0 fish and are included in the ocean age-1 category.

Table 1. Number of sets for the specified headrope depth range for each cruise.

Headrope Depth (m)	April 14 and May 1, 2	July 9, 10	Sept. 23, 24	Total
0-15	10	7	7	24
16-30	7	4	4	15
31-45	2	1	1	4
≥45	4	2	0	6
Total	23	14	12	

In April/May, virtually all the chinook were in the ocean age-1 category. A small number of ocean ages greater than one were also captured. The catch of coho was very small, indicating that few coho from the previous year were in the Sound, and that only a few of the smolts that would enter the ocean in 1997 had entered the areas fishable by our net. There were only six chum caught, all of which had entered salt water in the previous year (Table 2), indicating that juvenile chum that entered the Sound in 1996 probably left during the winter. In July, there were relatively large catches of ocean age-0 chinook and coho. Catches of chinook older than ocean age-0 were substantially reduced from April/May (Table 2). Juvenile chum catches were about 2/3 the size of the coho catch. A few juvenile and adult pink and sockeye were captured along with two Atlantic salmon that had clearly escaped from net pens, as their caudal fins were damaged and their gonads were deformed.

Table 2. Catch (numbers), average catch per hour (CPUE)[1], and standard deviations (SD) of salmon, 1997.

Species		April/May			July			September		
		Catch	CPUE	SD	Catch	CPUE	SD	Catch	CPUE	SD
Coho	ocean age-0	10	0.5	1.6	1696	282.5	580.7	38	7.3	8.8
	≥ocean age-1	26	1.5	3.1	2	0.3	0.8	15	2.5	4.6
Chinook	ocean age-0	2[2]	0.1	0.4	3189[3]	530.8	342.3	1545	282.4	255.4
	≥ocean age-1	495	28.7	40.0	93	16.1	28.7	19	3.3	6.4
Chum	ocean age-0	-	-	-	1063	177.6	213.8	2999	593.7	919.8
	≥ocean age-1	6	0.3	1.0	-	-	-	-	-	-
Pink	ocean age-0	-	-	-	4	0.7	1.3	-	-	-
	≥ocean age-1	1	0.1	0.2	1	0.2	0.6	-	-	-
Sockeye	ocean age-0	3	0.2	0.6	4	0.7	1.3	-	-	-
	≥ocean age-1	-	-	-	1	0.2	0.6	-	-	-
Steelhead	ocean age-0	9	0.5	2.1	-	-	-	-	-	-
	≥ocean age-1	-	-	-	-	-	-	-	-	-
Atlantic	ocean age-0	-	-	-	-	-	-	-	-	-
	≥ocean age-1	1	0.1	0.2	2	0.2	0.6	-	-	-

[1] CPUE includes all sets, with a headrope depth of ≤45 m, total catch includes all sets. A dash indicates no catch.
[2] Ocean age-0 is defined as ≤100 mm.
[3] Defined as 80 to 190 mm, (57% that were not measured were assumed to have the same age composition as those measured for fork length.

By September, catches of juvenile coho decreased dramatically compared to July. Only a few maturing coho that entered salt water in the previous year were found. There was an astonishing increase (3.4 times) in juvenile chum catches, which was equivalent to almost double the coho catch in July. Juvenile chinook catches declined by about 1/2 compared to June/July. No other salmon were captured in September, and catches of non-salmon species (not reported here) were almost zero (except for sandlance and age-0 herring). In all cruises, chinook, chum, and coho juveniles tended to be distributed throughout Puget Sound, however the greatest concentrations were in the Admiralty Inlet Area (Salmon Management Area 9).

Lengths

As mentioned previously, the samples of chinook captured in April/May have not been aged. A stratified sample of five fish from each cm-length class (n=91) indicated that between the lengths 80 mm and 350 mm, most (93%) were ocean age-1. There were two ocean age-0 chinook that had entered the Sound in 1997 (85 mm, 92 mm), and there were four that were stream-type chinook that had spent one winter in fresh water and thus were also ocean age-0, but larger. For abundance estimates only, we classified all chinook ≤190 mm from the April cruise as ocean age-1. The average lengths of the ocean age-1 chinook in April/May and ocean age-0 chinook in July and September were 249 mm, 129 mm, and 164 mm respectively (Table 3). (The unmeasured chinook in July [57%] were assumed to have the same fork length distributions as the measured percentage).

Table 3. Average fork lengths (mm) and standard deviations (SD) of Pacific salmon caught in Puget Sound in 1997. A dash indicates no data.

	Ocean Age	April/May mm	(SD)	n	July mm	(SD)	n	September mm	(SD)	n
Coho	0	137	(21)	10	208	(25)	849	259	(25)	38
	1	331	(35)	26	444	(24)	2	489	(43)	15
Chinook	0	89	(2)	2	129	(19)	1381	164	(27)	1079
	≥1	249	(114)	495	323	(144)	40	390	(116)	19
Chum	0	-		-	139	(17)	504	179	(15)	1017
	≥1	311	(61)	6	-		-	-		-

In April, there were small numbers of coho that were ocean age-1 and had an average length of 331 mm (Table 3). These coho were not present in the catches in June/July, but reappeared in September. Ocean age-0 coho were present in small numbers in April at an average length of 137 mm (Table 3). This age group was abundant in June/July, with an average length of 208 mm. By September, the few age-0 coho that remained had an average fork length of 259 mm. There was some indication that coho in south Puget Sound were smaller than those in the north (data not shown).

In July, the ocean age-0 chum had a mean fork length of 139 mm (Table 3) and by September, the mean length was 179 mm. The shape of the frequency distributions also changed from negatively skewed in June/July to positively skewed in September.

Index of Abundance

The abundance estimates for chinook, coho, and chum were made for the headrope depths from 0 to 30 m, and they are believed to be indices of minimal abundance. There were small catches below these depth strata (Figure 2), which were not included in the estimates. The omission of these catches is not considered to be an important error, because the largest error probably is our overestimate of catchability. In April/May, there were few ocean age-0 coho, chum, or chinook, consequently, the abundance estimates were extremely low. In July, all three species were abundant as ocean age-0 juveniles. There were very large estimates of chinook of 5.4 and 5.5 million in each stratum, totaling 10.9 million (Table 4). Coho were the second most abundant Pacific salmon in the catches at this time. Virtually all (91%) of the estimated 4.7 million coho were in the top 15 m. Chum were also concentrated in the top 15 m, with a total abundance of 2.86 million.

In September, the abundance index estimate of coho decreased to 180,000 fish. At the same time, the abundance index of chum increased almost four times to 13.9 million. Chinook salmon abundance remained high, but declined to 6.2 million (Table 4).

Table 4. Abundance estimates of ocean age-0 Pacific salmon in Puget Sound in 1997.

		April/May	July	September
Coho	0–15 m	12,300	4,300,000	40,000
	16–30 m	0	400,000	140,000
	Total	12,300	4,700,000	180,000
Chum	0–15 m	0	2,500,000	1,900,000
	16–30 m	0	360,000	12,000,000
	Total	0	2,860,000	13,900,000
Chinook	0–15 m	2,600	5,400,000	1,800,000
	16–30 m	0	5,500,000	4,400,000
	Total	2,600	10,900,000	6,200,000

We emphasize again that the abundance estimates are not believed to be true estimates of population size. They are, however, believed to be representative of relative abundance. We doubt that the assumed catchability of one is correct, which means that our abundance estimates are low. The index of abundance could be replaced by catch per unit effort (CPUE), which is an indication of abundance changes, because the changes are so large. Thus the dramatic change in coho abundance is probably real. The dramatic increase in chum abundance is also believed to be real. The increases in chum abundances from July to September probably represent movements from nearshore areas into the areas that were accessible by our vessel, the *W.E. Ricker*.

Coded-Wire Tag (CWT) Recoveries

All salmon were examined for missing fins. In addition to the samples collected in Puget Sound, we report the tagging location of coho released into Puget Sound in 1997 and captured in the Strait of Georgia, Juan de Fuca Strait, and off the west coast of Vancouver Island in October 1997 (Table 5). In June/July, there were adipose-clipped coho that we were unable to sample because we had technical problems with the CWT detector. Consequently, when sampling the two largest catches, all coho missing an adipose fin were taken back to the laboratory for processing (Table 6). In the two samples from July, in one set (n=988), 16% of the fish had an adipose fin missing and 18% of these fish had a CWT (Table 6). In the second set (n=408), 19% had a missing adipose fin, 27% of which had a CWT. In the April/May, and September cruises, all coho with a CWT were sampled.

Table 5. Recaptures of coded wire tagged (CWT) coho released into Puget Sound in 1997 for each brood year (BY).

In Puget Sound[1]							
	April/May	July			September		
	BY 95	BY 94	BY 95	BY 96	BY 94	BY 95	BY 96
Hatchery	1	0	60	11	1	1	0
Wild	0	0	8	0	0	0	0

[1] No Canadian CWT's found in Puget Sound

In the Strait of Georgia			
	June/July	September	October
	BY 95	BY 95	BY 95
Hatchery	4	9	1
Wild	0	1	0

In Juan de Fuca Strait									
	February		April	May		June/July		September	
	BY 94	BY 95	BY 94	BY 94	BY 94	BY 95	BY 96	BY 95	BY 96
Hatchery	17	1	18	11	8	11	1	1	1
Wild	0	1	3	0	3	1	0	0	0

Off the west coast						
	April	May/June	July		October	
	BY 94	BY 94	BY 94	BY 95	BY 95	BY 96
Hatchery	16	2	9	7	14	1
Wild	0	0	0	1	2	0

Table 6. Number of coho with missing adipose fins captured during the survey in Puget Sound.

Cruise	Total Number of Age-0 coho	Adipose fins missing	Number examined for CWT	Number of CWT's
April/May	10	3	3	2
July	1696	295	254	63
September	36	3	3	3

In Juan de Fuca Strait, ocean age-1, hatchery coho from Puget Sound were recaptured in February, April, and May. One coho from the 1995 brood year was recaptured in February. Releases in 1997 were recaptured in June/July and September. Off the west coast, the 1997 releases were recaptured in July and October (Table 5). No coho with CWT's from Canadian hatcheries were recaptured in Puget Sound, although one coho with a left pelvic clip was found in September. It is apparent that coho from Puget Sound moved out of the Sound and into the Strait of Georgia, Juan de Fuca Strait and off the west coast as early as July.

We captured a large number (119) of CWT chinook in Puget Sound in July that were from the 1996 brood year and released into the Sound in 1997 (Table 7). Most tags were from the Hupp Springs (24) and Grovers Creek (22) facilities. Large returns were also from Soos Creek (15), Washington Department of Fish and Wildlife (16) and Nisqually (16) releases. These releases were also abundant in the September catches. Catches of chinook from the 1996 brood year (1997 year of ocean entry) outside of Puget Sound were not large (Table 8), relative to previous year's releases and to coho recoveries. Although it is difficult to interpret tag recovery data, we propose that the CWT results for chinook indicate that fewer chinook were moving out of Puget Sound in the summer. This is consistent with our observation of a relatively large abundance of chinook in Puget Sound in September.

Table 7. Number of chinook with missing adipose fins captured during the survey.

Cruise	Total Number of Age-0 chinook	Adipose fins missing	Number examined for CWT	Number of CWT
April/May	2	0	2	0
July	3251	150	150	128
September	1559	74	74	74

Table 8. Recaptures of coded wire tagged (CWT) chinook, released into Puget Sound in 1997 for each brood year (BY).

	In Puget Sound						
	April		July			September	
	BY 94	BY 95	BY 94	BY 95	BY 96	BY 95	BY 96
Hatchery	3	63	1	6	119	11	61

	In the Strait of Georgia					
	April		May/June	July		October
	BY 94	BY 95	BY 95	BY 94	BY 95	-
Hatchery	10	2	3	2	3	0

	In Juan de Fuca Strait							
	February	April		May/June		July	September	October
	BY 95	BY 94	BY 95	BY 94	BY 95	BY 96	BY 96	-
Hatchery	11	3	4	4	6	1	2	0

Table 8 (continued). Recaptures of coded wire tagged (CWT) chinook, released into Puget Sound in 1997 for each brood year (BY).

	Off the west coast						
	April		May/June		July	October	
	BY 94	BY 95	BY 94	BY 95	BY 96	BY 94	BY 96
Hatchery	11	5	1	2	1	1	1

Stomach Content Analysis

In the three cruises, a total of 1004 stomachs from the combined coho, chum, and chinook samples were examined (Table 9). The volume of the stomach contents was estimated and washed into a small tray where the contents were identified using a 10x magnifying glass. All samples were from ocean age-0 fish, except the April chinook samples, which were defined to be ocean age-1 as described earlier. All contents were determined by a person with extensive experience identifying marine plankton.

In general, the major food items of coho and chum were similar, but varied among cruises. In April/May, euphausids dominated the diets of all three species. In July, coho and chum fed heavily on crab larvae (Table 9). For chum, the predominant stomach item appeared to be mostly digested crab larva. In September, amphipods were the dominant item in the stomachs of coho and chum. There were differences among the less important food items. After April, 1/5 of the coho diet of was fish, while chum did not feed on fish. About 1/5 of the chum diet was classified as miscellaneous species that were not consumed by coho or chinook. Chinook fed much more on fishes than the other two species. The other key items in their diet were similar to major items consumed by coho and chum.

Table 9. Stomach contents as a percentage of the total volume from all samples.[1]

	April/May			July			September		
Item	coho	chum	chinook	coho	chum	chinook	coho	chum	chinook
Euphausiids	92.7	100	67	0.5	0	6.8	8.6	5.1	3.5
Amphipod	2.2	0	0.6	0.4	0.7	1.6	60.0	47.2	9.7
Crab larva	0.7	0	0	76.3	32.2	19.4	12.4	5.6	12.2
Fish remains	0.3	0	31.4	22.1	0	68.4	17.4	0	71
Digested	3.9	0	0.4	0	35.8	1.2	1.2	17.8	0.6
Copepod	0	0	0.1	0	12.1	0.7	0	0.5	0.3
Miscellaneous[2]	0	0	0	0	18.4	0	0	23	0
Number examined	10	4	336	149	19	124	38	120	204
Number empty	0	0	26	15	6	15	6	16	34
Avg. volume of fish with contents (cc)	0.7	1.6	3.9	2.6	0.1	0.8	2.0	0.4	1.0

[1]Total percentages may not add up to 100% as some minor food items are not listed.
[2]Miscellaneous includes: chaetognath, *Oikopleura*, ctenophore.

Condition Factors

Condition factors were calculated as the weight (g) x 100 divided by the length (cm) cubed, and averaged for each species for the July and September cruises. Condition factors remained about the same among cruises for chinook and chum. The condition of coho decreased from July to September (Table 10), although this difference was not significant ($p>0.05$).

Table 10. Condition factor $^{W}/_{L}^{3}$ x 100 and standard deviation (SD) for ocean age-0 Pacific salmon. Averages of lengths and weights are for fish used to measure condition factors.

Species	Date	Average Fork Length (mm)	Average Weight (g)	Average Condition Factor	S.D	n
Chinook	July 1997	135	30	1.124	0.168	249
	Sept. 1997	168	62	1.149	0.159	257
Coho	July 1997	211	126	1.313	0.387	167
	Sept. 1997	259	223	1.245	0.114	38
Chum	July 1997	146	32	1.010	0.140	19
	Sept. 1997	183	63	1.005	0.069	120

Discussion

Our study of Pacific salmon in Puget Sound involved collecting a relatively few samples three times in one year. Thus, our conclusions need to be considered as information that improves our understanding of some aspects of the marine life history of Pacific salmon and raises more questions about other aspects. The study in Puget Sound was part of a larger study of the factors that regulate the abundance of coho and chinook in the ocean.

In the Strait of Georgia, coho do not leave until the late fall. Thus, it was unexpected to observe the disappearance of coho from the Puget Sound catches by September. The associated large increase in juvenile chum salmon catches was similar to the changes that occur in the fall in the Strait of Georgia (Beamish and Folkes 1998), except that coho do not leave until later in the Strait of Georgia (Beamish et al. 1998a). The abundance of chum relative to coho in Puget Sound increased from 1.6 times lower in June/July to 82 times higher in September. The catches of CWT-tagged juvenile coho in Juan de Fuca Strait in June/July and off Vancouver Island in November indicated that coho probably left Puget Sound and moved offshore throughout the summer. We observed that about 15% of the coho in the Strait of Georgia in September were from Puget Sound. Because our abundance estimates of coho in the Strait of Georgia in September 1997 were lower than for Puget Sound in July, (Beamish et al. 1998a), we think that most of the Puget Sound coho moved into Juan de Fuca Strait and not into the Strait of Georgia.

Coho and chum salmon fed on similar items and were similar in size. Thus, it was possible that the movement of juvenile chum salmon from the nearshore areas into the open water of the Sound (where they are vulnerable to our nets) was associated with the movement of coho out of the Sound. If we compare our estimate of 5.7 million juvenile coho in June/July with the estimated production of 14 million hatchery smolts and 6 million natural smolts (WDFW 1998), it may appear that about 75% of the smolts died by June/July. However, we stress again that the estimate of 5.7 million is only a relative estimate at this time. Certainly by September there were less than 1% of the coho that entered the Sound earlier in the year. The size of coho and the condition of coho in Puget Sound in June/July is larger and better than observed for coho in the Strait of Georgia ($\overline{FL} = 174\,mm; \overline{CF} = 1.14$), however there was evidence that the condition of coho in Puget Sound declined by September.

It is an important observation that large numbers of chum and chinook remained in Puget Sound until at least September without a change in their condition factor. This indicates that food was available for these species and presumably in abundance, because there were large numbers feeding and there was no evidence of starvation. Coho therefore may have left the Sound for reasons associated with the behaviour of chum. The concept of crowding of coho could lead to a reduction in appetite and in growth rate. A reduced rate of growth could be a stimulus to leave the area. Although the reason or reasons remain unknown, it is possible that the movement out of Puget Sound in the late summer and out of the Strait of Georgia in the late fall may have some common causes. In the Strait of Georgia, movement out of the Strait has been associated with ocean and climate conditions (Beamish et al. 1994; Beamish et al. 1998b).

There also has been a change in the behaviour of juvenile chum salmon in the Strait of Georgia resulting in large abundances relative to coho remaining in the Strait of Georgia in the fall (Beamish and Folkes 1998). Although the abundances are not as large as in Puget Sound, there is a similarity in the behavior of chum. It is possible that the movement of coho out of the Strait of Georgia is also influenced by the accumulation of juvenile chum in the coho feeding areas in the fall. If there is an association, there may be opportunities to influence both coho behavior and marine survival. It would be interesting to learn whether there is any relationship between the large numbers of chum that remain in the Strait of Georgia later in the year than in the past (Beamish and Folkes 1998) and those found in Puget Sound in September. Techniques are available to answer many of the questions resulting from this study.

The large abundance late in the year relative to the final returns is an indication that we need to know more about the factors regulating carrying capacity. Thus, the view that final abundance is determined shortly after entering the ocean is not consistent with our observations. Why do coho leave so early in the year, and does this movement contribute to higher levels of marine mortality according to the mechanisms proposed by Beamish and Mahnken (1998)? Although we cannot control the natural changes in the ocean ecosystem, we do have control over the number of smolts that compete in this ecosystem, and we need to know whether a reduction in releases could improve the marine survival of naturally spawning coho.

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Coho and Climate: Forecasting Marine Survival of Puget Sound Coho Salmon Using Climate Indices

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Introduction

Each year the State of Washington makes a forecast of the number of adult coho salmon (*Oncorhynchus kisutch*) that will return to Washington waters. The forecast is conducted jointly by the Washington Department of Fish and Wildlife (WDFW) and the Northwest Indian Fisheries Commission (NWIFC) in January and February of each year to allocate fishing effort to commercial fishers, native tribes, and sport fishers.

Estimates are made of adult returns for the summer months (July–September) to Puget Sound. Estimates of the total number of hatchery smolts (juvenile salmon) entering the marine environment are multiplied by a five-year average of marine survival (% of smolts that return as adults; hereafter MS) of coho to estimate the number of returning adults. In the early 1990s, this method has over-forecasted MS, revealing a weakness in the forecasting technique, the application of the five-year average of MS. The way in which interannual climate-variability influences MS of Puget Sound coho salmon needs to be understood to improve the forecast.

Evidence from the Oregon coast suggests that the majority of marine mortality occurs in the first three months of ocean residency (W. G. Pearcy, pers. comm. Feb. 1997). Beamish, et al. (1995) found synchronous timing of an increase in mean temperature of the Strait of Georgia and MS of hatchery-reared chinook salmon released into the Strait of Georgia. Francis and Hare (1994) found a relation between a climate indices and subsequent returns of salmon in Alaska, adjusted for year of entry. Holtby, et al. (1990) found that growth during the first few months of life in the ocean was well correlated with total marine survival. This evidence suggests that the effects of climate variability on salmon are manifested in the first year of ocean residency.

Spatial and temporal variations exist at the regional scale in coho salmon MS, a measure of salmon productivity. Coronado-Hernandez (1995) demonstrated clearly that coho salmon originating in inland waterways (Puget Sound and Strait of Georgia; hereafter PS and GS, respectively) have higher MS (long-term average ≈ 8.5%) than coastal coho (Washington coast and west coast of Vancouver Island, hereafter WC and WCVI, respectively) (long-term average MS ≈ 3.9%). PS coho MS peaked at 17% in 1984, and SG coho MS peaked at 26% in 1973. Coronado-Hernandez (1995) calculated MS from coded wire tag (CWT) data dating to 1971. The inland waterways of the PNW must act like a buffer from the harsher conditions of the coast.

Why do coho salmon from Puget Sound have a different pattern of survival than coho salmon from the Strait of Georgia, and how does climate variability regulate these patterns? I postulate that the differences in patterns of coho MS result from differences in localized oceanographic conditions at the time and place that juvenile salmon enter the marine environment. The localized oceanographic conditions (strength of upwelling [coastal areas], freshwater input [inland waterways], temperature, primary production, etc.) are an integration of climate variability.

Objectives

The objectives of my research are to:

- Develop an index of marine survival;
- Characterize the climate of Puget Sound in:
    - poor marine survival years, and
    - good marine survival years; and
- Develop a forecast model of marine survival based on the climate of Puget Sound.

Puget Sound and Climate Variability

Puget Sound is chosen as the first step of the investigation because it stands out as an anomaly, both regionally (salmon have higher survival than the coast), and sub-regionally (salmon have different patterns of survival than nearby areas, such as the Strait of Georgia). To illustrate how coho salmon are affected by climate variability, it is helpful to develop a conceptual model. Puget Sound, a fjord estuary, has an input of fresh water and an input of salt water. Changes in these inputs can have dramatic effects on both circulation and mixing patterns.

Ebbesmeyer et al. (1988) described decade-scale changes in deep-water input into Puget Sound. The paper linked decadal changes in the atmosphere to changes in the physics of the marine waters of Puget Sound. When the Aleutian Low pressure center is positinioned over the eastern Pacific Ocean, storms drop less precipitation over Washington. This causes a decrease in freshwater input into Puget Sound, which in turn causes a rearrangement of the density profile of the Strait of Juan de Fuca and decreases the difference in density across the entrance (Admiralty Inlet) of the Puget Sound basin (Ebbesmeyer et al., 1988). This difference in density causes the influxing oceanic water to enter along the bottom. In the opposite regime, when the Aleutian Low is centered over the western Pacific, the influx of oceanic water occurs at mid-depth.

Changes in the timing and magnitude of inputs (fresh water, salt water) to Puget Sound cause changes in the conditions necessary for plankton production (both phytoplankton and zooplankton). Optimal conditions for phytoplankton blooms arise when a balance occurs between mixing, light, and stratification (Strickland 1983, p. 45). Mixing is important for bringing nutrients to the surface, stratification is important for keeping phytoplankton near energy from the sun, and light is necessary to stimulate photosynthetic processes in phytoplankton.

Forecast Model

The forecast input variables need to be easily accessible to WDFW and NWIFC to eliminate costly sampling protocols. It is important to note that a forecast is only being made on MS of coho salmon, not a forecast of oceanographic variables. The forecast will be based on oceanographic conditions that have occurred and have been measured.

Preliminary results suggest that stream flow (freshwater input) into Puget Sound is higher in the spring of good coho-MS years, and shows a lower peak in the spring in poor coho-MS years. Sea surface temperature is cooler in good MS years, and warmer in poor MS years. Upwelling is generally higher during the summer of ocean entry in good MS years, and lower during the summer in poor MS years. These results, although preliminary, suggest that conditions for good marine survival are correlated with cool, wet years in the Puget Sound region. Initial model formulations have shown a significant improvement to the current forecast model by using a climate index incorporating stream flow and sea surface temperature.

Discussion

Puget Sound coho marine survival appears to be driven by changes in the oceanographic and climatic conditions in the Puget Sound region. Good-survival years are associated with high spring stream flow, high April-15th snow pack, cool sea surface temperatures, cool air temperatures, and strong summer upwelling. It is hypothesized that changes in the mixing and circulation regimes of Puget Sound have altered the timing and magnitude of primary production peaks, and that coho salmon are "missing" this peak in primary (and ultimately secondary) production. It is possible that changes in salinity drive coho out of Puget Sound, thereby causing them to miss the spring plankton bloom, but few data are available to support this hypothesis. I propose that coho are missing the peak of the spring bloom because timing of coho ocean entry is constant, while the timing of the spring bloom is occurring earlier.

As more is learned of the intricate web of life that spans the thin biosphere of Earth, the more evident it becomes that no single branch of science can begin to answer even the simplest of ecological questions. Fishery science is not immune from this affliction and is a science ripe for interdisciplinary research. Investigating the link between the living and physical components of large ecosystems is necessary if decision-makers are to ensure a long-term yield from a finite resource. Understanding the range of variation both in the physical environment and the parallel variability of biological systems is tantamount to proper "management."

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The Distribution and Abundance of Nearshore Rocky-Reef Habitats and Fishes in Puget Sound

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Introduction

Rockfishes (*Sebastes* spp.), lingcod (*Ophiodon elongatus*), and kelp greenling (*Hexagrammos decagrammus*) are the most popular bottomfish species targeted by recreational anglers in Puget Sound. In nearshore waters, these species typically inhabit rocky and irregular bottoms, including natural reefs, artificial reefs, shipwrecks, jetties and breakwaters. A large proportion of the recreational bottomfish effort in Puget Sound occurs in the nearshore environment. Thus, in order to provide adequate protection and management for the species and their habitats, it is critical that fishery managers know how much rocky-reef habitat exists and to what extent these areas are utilized.

Since 1993, the Washington Department of Fish and Wildlife (WDFW) has used a video-acoustic technique (VAT) to conduct *in-situ* fish population surveys throughout the inland marine waters of the Washington. The primary objective of the VAT surveys is to provide regional estimates of nearshore rocky-reef fish populations. By using an underwater video camera, it is possible to characterize the habitat observed at each survey station. Thus, a secondary objective of the VAT surveys is to quantify the type and amount of the various habitats encountered. Using geographic information systems (GIS) software, the habitat data collected during these surveys will be used to produce maps of the nearshore rocky-reef habitats within Puget Sound. These habitat data will serve as the basis for future fish population surveys and habitat assessment studies. By identifying the rocky-reef habitats and major concentrations of rocky-reef fishes, smaller scale surveys will be designed to provide more accurate population assessments and produce more detailed maps of individual rocky reefs in Puget Sound.

Methods

Habitat Identification

Prospective rocky-reef habitats within the interior marine waters of the Washington east of the Sekiu River (hereafter referred to as Puget Sound) were initially identified using 1:25,000 and 1:40,000 scale National Ocean Service (NOS) charts, which characterize bottom types and other habitat features. Each survey area, defined as a chart, was categorized into areas likely and not likely to contain reef fish habitat at depths from 0 m to 37 m below mean lower low water (MLLW). Unlikely reef habitat was defined as chart areas with sand or mud on flat, featureless bottom. Potential reef habitat included gravel, rock, boulders, areas of steep relief, sewer outfalls, obstructions, wrecks, and artificial reefs. Identification of potential reef habitat was augmented by knowledge of productive (or formerly productive) fishing areas obtained from WDFW personnel and local anglers. Areas identified as potential habitat were incorporated into a stratified-systematic survey design and digitized on a computer to provide estimates of potential reef area.

Video Survey

For surveys conducted in the San Juan Archipelago (SJA) in 1993 and 1994, potential rocky-reef habitat was partitioned into 1-km segments along the shoreline and stratified by depth into a shallow zone (0–18 fathoms) and a deep zone (19–37 fathoms). Beginning at a random starting point, every fourth station within the SJA was sampled in 1993, with the effort doubled to include every other station in 1994.

In 1994, stations along the Strait of Juan de Fuca (SJF) were established and sampled in a similar manner to those of the SJA. However, the NOS charts were imprecise and included areas

where the habitat type was unknown or poorly described. Areas of known reefs were sampled at 0.5-km intervals and areas of unknown habitat were sampled every 1–2 km along the shore. The surveys in this area also included shallow and deep depth strata, as in the SJA surveys.

For the VAT surveys of central and south Puget Sound (CPS and SPS) in 1995 and Hood Canal (HC) and the SJF in 1996, potential reef habitat was stratified on the basis of expected habitat quality. "High" stratum stations included natural reefs, artificial reefs, breakwaters, sewer pipes and other known areas of rockfish and lingcod aggregations. "Medium" stratum stations consisted of habitats with steep slopes, kelp beds, cobble bottoms, or other potential habitats. Stations in the "Low" stratum included areas where the habitat type was unknown but offered some possible rockfish or lingcod habitat. High-stratum stations were defined around a grid 0.19 km square (= 0.036 km^2), and Medium-stratum stations were defined around a square grid of 0.39 km (= 0.152 km^2). Low-stratum stations were defined either as a 1.0-km station along the shore similar to the station pattern in the SJA, or in the case of offshore banks and reefs, around a square grid of 0.77 km (= 0.592 km^2).

For surveys conducted in 1993 and 1994, all camera deployments were made as close to the geographic center of the station as possible, with target depths of 7 fathoms and 15 fathoms in the shallow and deep strata, respectively. No depth strata were used in 1995 and 1996; instead, camera deployments were made at a pre-selected random depth within each station square.

The video platform for all surveys consisted of a tripod, 1.5 m in height, constructed from 2 cm diameter steel reinforcing rods (rebar). Weights were attached to the bottom of the platform to improve stability during high current (<1.5 knots) deployments. The total weight of the camera platform and attached weights was approximately 75 kg. A Remote Ocean System PT-25 pan and tilt motor was suspended from the apex of the tripod to which a Deep Sea Power and Light underwater black-and-white television camera and light was attached. A 2-cm kevlar line attached to the platform was used to raise and lower the cage from a support vessel. A 2.5-cm multistrand underwater electrical cable was attached to the camera, light, and motor and extended to the vessel where it was attached to a Remote Ocean System controller.

The Research Vessel *R/V Molluscan,* a 12-m long, diesel-powered, displacement-hull vessel with a draft of 1.7 m was used to deploy the video platform during all surveys. A hydraulic deck winch mounted on the aft deck was used to deploy the kevlar line through a gantry mounted around a 1.5-m port in the transom. The gantry allowed the lift point to clear the camera platform from the deck and suspend the camera platform approximately 2 m away from the stern. The electrical cable was deployed and retrieved by hand, and was stacked on deck near the transom. For surveys conducted in 1993, 1994, and 1995, the support vessel was equipped with a Magellan Differential Geographic Positioning system (DGPS). This system was upgraded to a Northstar 951 DX DGPS chart plotter for the 1996 survey, providing more accurate geographic position fixes and allowing for more efficient survey planning and execution. Other equipment used during the surveys included a video depth sounder, radar, and LORAN.

The motor, camera, and light were remotely controlled by an operator aboard the *R/V Molluscan.* A minimum of two 360_ sweeps of the viewing plane were conducted during each camera deployment. During each sweep, the camera was tilted up and down to screen the entire field surrounding the platform within 2 m of the bottom. Each sweep lasted about two minutes and three sweeps were usually attempted at each deployment. Total deployment time, including descent and ascent, ranged from seven to 12 minutes, depending upon the depth of deployment. When current or boating conditions were severe, only two camera sweeps were conducted, but at least two sweeps were required for the deployment to be valid. When the camera platform was overturned or other conditions prevented two successful sweeps, the platform was redeployed for another trial. All activities including deployment, platform positioning, camera sweeps, and retrieval were recorded on Hi-8-mm video tape with a Sony EVS 3000 video cassette recorder. Videotapes were labeled and archived for laboratory analysis.

In the laboratory, VAT survey tapes were reviewed and the fishes and commercially important invertebrate species were identified and enumerated for each camera sweep. Only fishes observed within 2 m

of the bottom were counted. An estimate of the visible range of the camera was made for each deployment. Visibility estimates were based on scuba observations and measurements of distance, camera angle, and water clarity. Habitat information collected from the videotape included dominant and sub-dominant substrate, vertical relief, habitat complexity, and dominant and sub-dominant biological cover. Substrates were divided into four major categories, with the dominant substrate being that which comprised the majority of the area viewed by the camera. If more than two substrate types were present, only the two most abundant types were recorded in the database. Rocky-reef habitat included bedrock, boulder, and hardpan (e.g., clay, sandstone) substrates. Cobble and gravel substrates were classified as coarse grain habitats, with sand and mud bottoms comprising fine grain habitats. The "artificial" category included artificial reefs composed of tires, concrete rubble, and/or quarry rock, shipwrecks, and other sunken man-made structures (e.g., docks, pilings, log rafts, sewer pipes, etc.) Vertical relief was determined based on the relative elevation of the surrounding habitat to the camera. Habitat complexity was a subjective measure, and was visually estimated as the amount of crevice space 10 cm or greater within the survey plot.

In 1993 and 1994, the water surface area of rocky-reef habitat within each survey area was estimated by multiplying the proportion of stations containing rocky-reef substrate by the total survey area. At selected stations in 1995 and 1996, particularly small natural reefs, artificial reefs, shipwrecks, and sewer pipes, the approximate boundaries of the observed feature were plotted using the *R/V Molluscan*'s bottom sounder and DGPS. These boundaries were recorded in the GIS database and the area calculated. For the remaining stations, the area encompassed by the grid square was used as the default station area. The total amount of rocky-reef habitat was then calculated by summing the areas of all stations where rocky-reef substrate was observed.

Density estimates for each taxon were made by dividing the number of individuals (C) for each taxon observed during the last valid camera sweep by the area viewed during the deployment. The viewing area (a) of the deployment was determined by using the estimated visibility (V) as the radius in the area of a circle. For each taxon, density (f) was estimated as:

$$f = \frac{C}{a} = \frac{C}{(\pi V^2)}.$$

For each nautical chart or management region, representing an independent survey area, the stratum estimates of video fish density were averaged among stations and variances computed for the stratified systematic sample (Shaeffer et al., 1986). Where f_{ij} is the fish density observation for the i-th of n stations in the j-th stratum, A_j is the area of the j-th stratum, N_j is the species population estimate of the j-th stratum, and $Var(N_j)$ is the population variance of the population estimate of the j-th stratum:

Population estimate: $$N_j = A_j \bar{f}_j = A_j \sum_{i=1}^{n=i} \frac{f_{ij}}{n}$$

Population variance: $$Var(N_j) = A^2 Var(\bar{f}_j) = A^2 \sum_{i=1}^{i=n} \frac{(f_{ij} - \bar{f}_j)^2}{(n-1)}$$

Results

From 1993 to 1996, a total of 2,008 VAT camera deployments were accomplished in the six Groundfish Management Regions (GMRs) surveyed in Puget Sound (Table 1, Figure 1). Coarse grain and fine grain substrates were commonly encountered during all surveys. Stations with dominant rocky-reef substrates included boulder fields, scoured bedrock or clay bank walls, rocky ledges, and bedrock outcroppings. At stations where rocky-reef substrates were sub-dominant, the habitat consisted largely of gravel or sand bottoms with widely scattered boulders or small bedrock ridges.

In the SJA, nearly 55% of the stations surveyed contained rocky-reef habitat as either the dominant or sub-dominant substrate, resulting in an estimated rocky-reef area of 111.8 km^2 (Table 2). Rocky-reef habitat in the SJF was estimated to be 95.3 km^2 in 1994, and comprised 19% of the total area surveyed. In

1996, the area of rocky-reef habitat in the SJF was estimated to be 34.4 km^2, or about 36% of the total survey area. Rocky-reef habitat in central and south Puget Sound made up 18% of the survey area in these regions, with an estimated area of 9.9 km^2, about 75% of which was in the CPS region. Nearshore rocky-reef habitat was sparse in the GB and HC regions, with estimates of 2.7 km^2 and 1.0 km^2, respectively.

Table 1. Number of camera deployments by region and year for WDFW VAT surveys.

Region and Year	Number of camera deployments
San Juan Archipelago 1993	228
San Juan Archipelago 1994	407
Strait of Juan de Fuca 1994	194
Central Puget Sound 1995	367
South Puget Sound 1995	177
Gulf-Bellingham 1995	50
Strait of Juan de Fuca 1996	461
Hood Canal 1996	124

The area estimates of rocky-reef habitat were lower in most regions when only the dominant substrate was used for the area calculation. The amount of rocky-reef habitat in the SJA dropped over 30% to 76.5 km^2, while the 1994 estimate for the SJF was reduced over 80% to 13.6 km^2. Rocky-reef area estimates were 50% to 80% lower in the other regions except HC, which did not change. Artificial substrates were observed in four of the regions, but made up only a small proportion of the total survey areas (Table 2).

Table 2. Estimated area (km^2) of all habitat types sampled during the nearshore VAT surveys.

	Substrate area (km^2)				
Region/Year	Rocky-reef total	Rocky-reef dominant	Coarse	Fine	Artificial
SJA 1993–4	111.8	76.5	36.0	50.6	---
SJF 1994	95.3	13.6	132.2	274.6	---
CPS 1995	7.6	2.6	12.5	18.8	0.4
SPS 1995	2.3	1.2	4.7	9.5	0.6
GB 1995	2.7	0.6	0.2	4.7	---
SJF 1996	34.4	7.5	28.0	33.7	0.3
HC 1996	1.0	1.0	1.4	11.9	0.2

Frequencies of occurrence for the target species varied by region, but never exceeded 18% (Figure 2). Copper rockfish *Sebastes caurinus* were the most commonly encountered target species, with the exception of the SJA in 1993 and the SJF in 1994. Quillback rockfish *S. maliger* occurred at about one-fourth to one-third the frequency of copper rockfish except in the CPS region, where they were observed in similar frequencies. Lingcod *Ophiodon elongatus* were observed on 1%–4% of all camera deployments, with the highest frequencies seen in the SJA in 1994 and in the SPS in 1995. Frequencies of occurrence of kelp greenling *Hexagrammos decagrammus* were similar to those for lingcod, ranging from 1% in SPS and HC to 10% in the SJA (1993). Black rockfish *S. melanops* were rarely seen, although when observed, they usually occurred in schools of 10 to 40 or more fish. The highest encounter rates were in the SJF in 1996 (3% FO), with the majority of occurrences in kelp beds (*Nereocystis leutkeana* and *Pterygophora* spp.) None of the primary target species were observed in the Gulf-Bellingham region.

Most observations of the target species occurred at stations where rocky substrates were present (either as the dominant or sub-dominant substrate.) For example, rocky-reef habitat was present at 94% of the stations with copper rockfish and at 74% of the stations with lingcod. However, copper rockfish and lingcod were observed at less than 20% and 5%, respectively, of all stations containing rocky-reef substrates. By region, copper rockfish were present at 3% of the rocky-reef stations in the SJF in 1994 and at 65% of all rocky-reef stations in the HC region (Figure 3). In the other regions, frequencies of

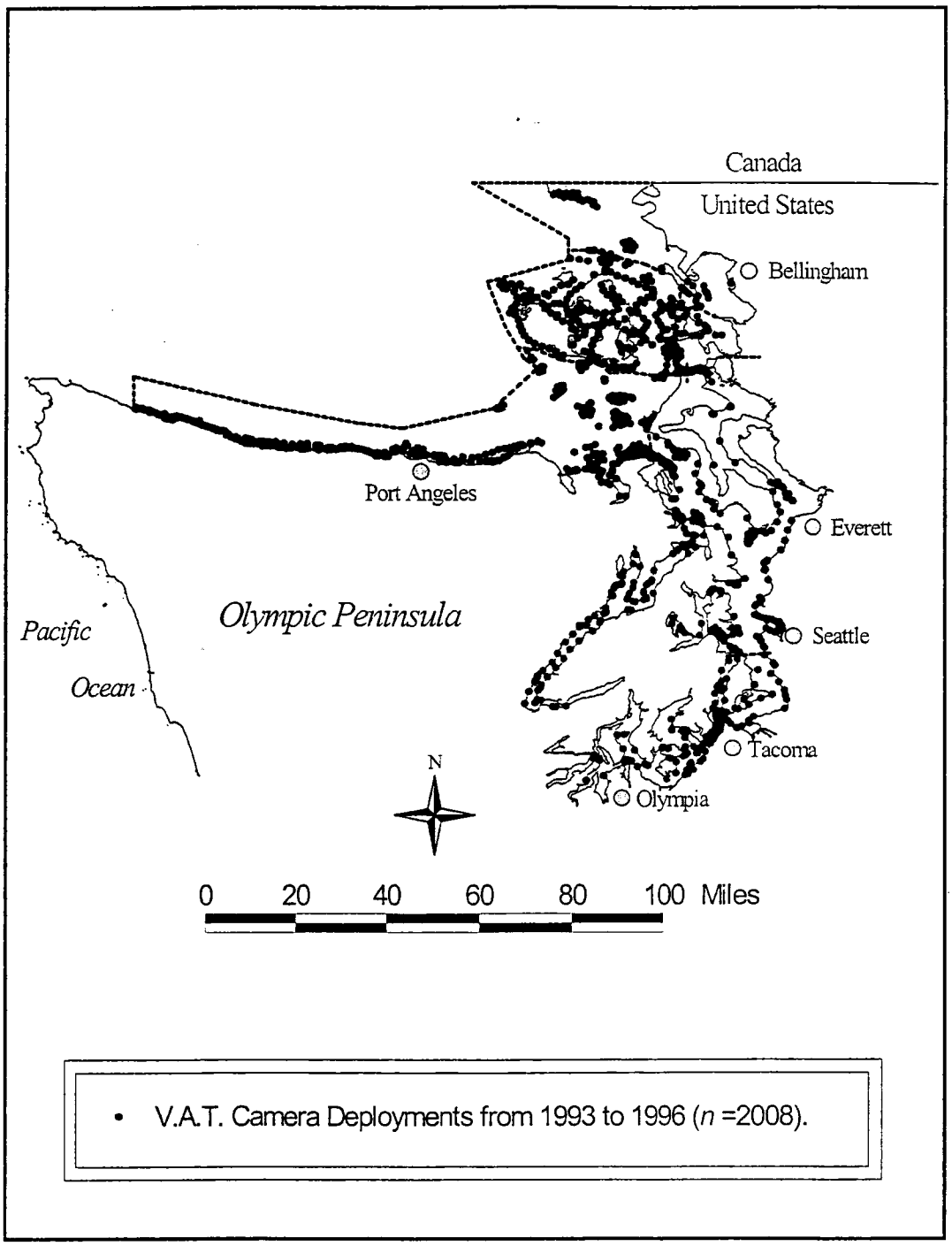

Figure 1. Locations of VAT camera deployment during nearshore VAT surveys, 1993–1996.

occurrence ranged from 11% to 27%. Copper rockfish were relatively common on artificial substrates in three of the regions, occurring on 33% to 43% of these substrates. In the CPS, SPS, and HC regions, about half of the artificial substrate stations sampled were reef structures constructed for the purpose of attracting fish. In the SJF (1996), the artificial substrates sampled included shipwrecks, ballast rock mounds, and marina breakwaters. Copper rockfish were less common on artificial substrates in the SPS region (18% FO), which consisted mainly of sewer discharge pipes and tire reefs.

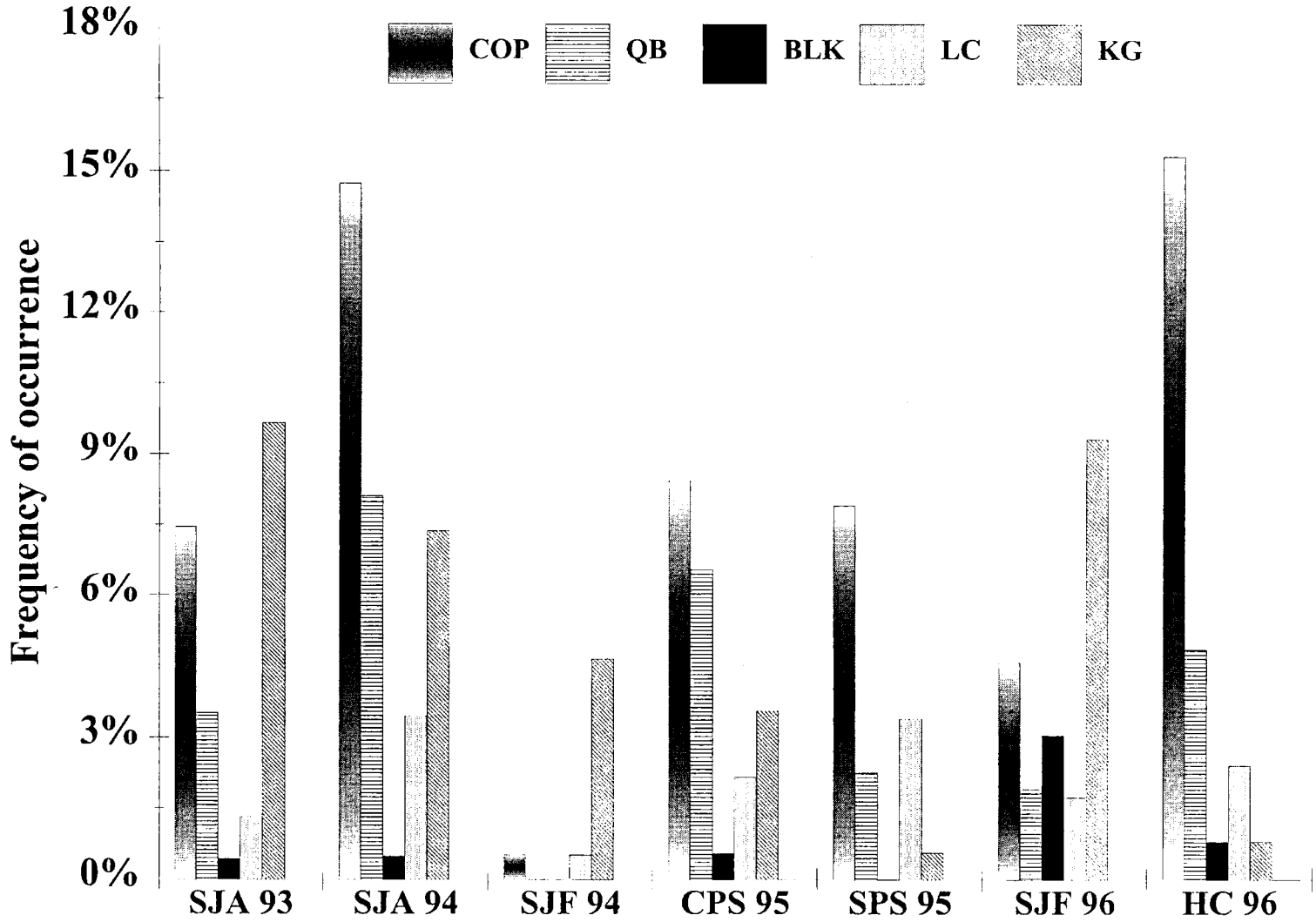

Figure 2. Frequency of occurrence of five bottomfish species observed during the nearshore VAT surveys by region. (COP = copper rockfish, QB = quillback rockfish, BLK = black rockfish, LC = lingcod, KG = kelp greenling).

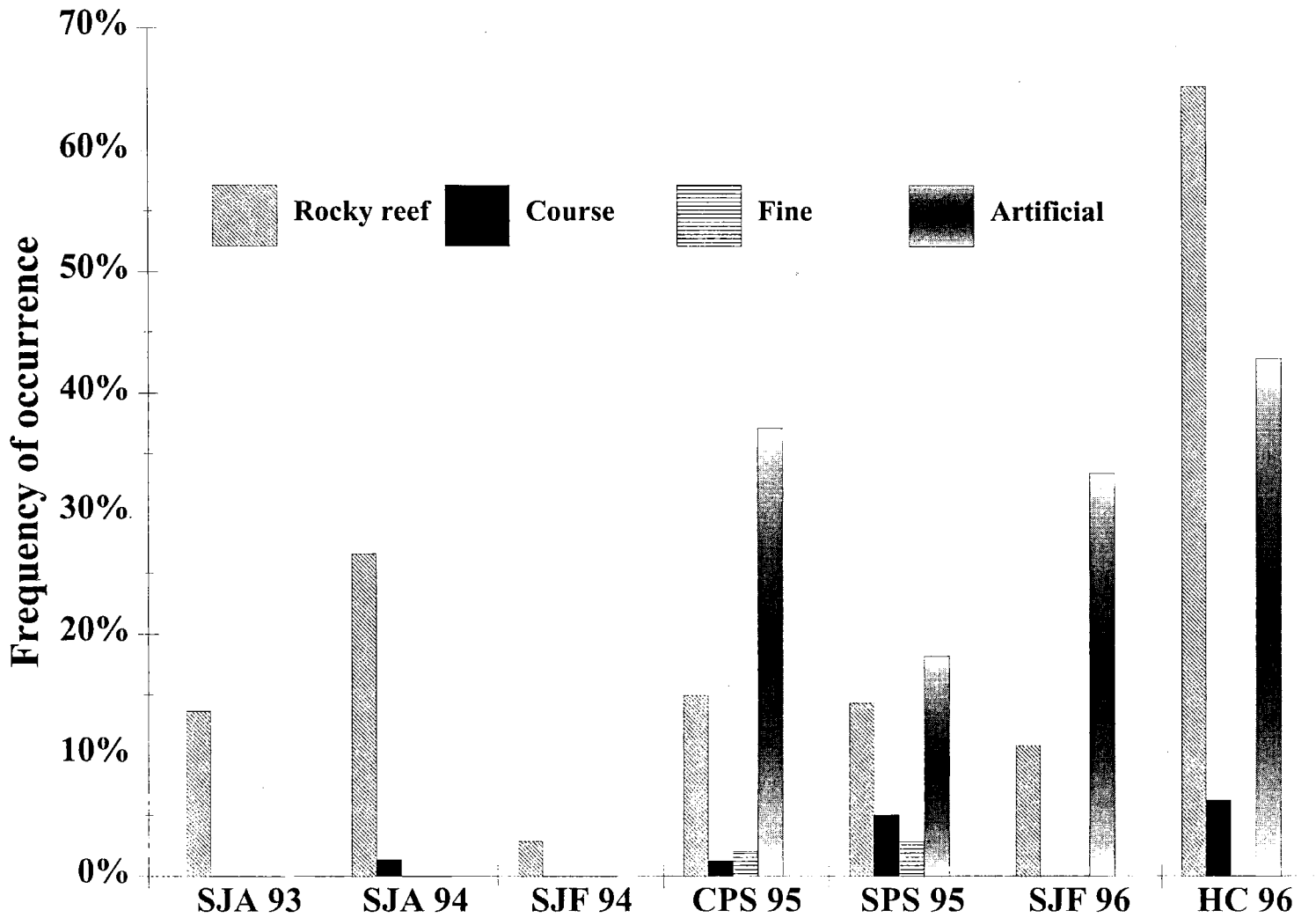

Figure 3. Frequency of occurrence of copper rockfish by habitat type and region.

Population estimates for copper rockfish ranged from 87,000 fish in HC to 3.6 million fish in the SJA (Table 3). About 500,000 copper rockfish were estimated from the 1994 survey of the SJF, but that estimate was reduced to 0.1 million fish in the 1996 survey. Estimates for the CPS and SPS were similar, with just over 100,000 copper rockfish in each region. Quillback rockfish were most abundant in the SJA (1994, 1.9 million fish) and substantially lower in the other regions. Unlike the other regions, quillback rockfish were more abundant than copper rockfish in CPS, with an estimated 202,000 fish. Lingcod were most abundant in the SJA, with approximately 313,000 fish inhabiting nearshore reefs. Lingcod abundance differed in other regions and was lowest in HC, with an estimated 16,000 fish. Black rockfish abundance was very low in all regions except the SJF (1996), where the nearshore population was estimated to be about 434,000 fish. Kelp greenling also showed differing population estimates among regions, but were most abundant in the SJF (1996), with about 363,000 fish in this region.

Coefficients of variation (C.V.) (weighted by chart for each region) were highly variable. Except for the SJF in 1996, copper rockfish C.V.'s were relatively low, ranging from 23.1% to 41.9% (Table 3). In the SJA, copper rockfish C.V.'s declined from 35.6% in 1993 to 23.1% in 1994 when sampling effort was essentially doubled. Quillback rockfish C.V.'s were slightly higher than for copper rockfish, and showed a similar decline in the SJA, dropping from 45.1% in 1993 to 32% in 1994. Black rockfish were only observed in the SJA, SJF, and CPS regions, and had C.V.'s between 51% and 73%. Lingcod C.V.'s were lowest in the SJA (1994), CPS and SPS regions, from 31.6% and 45.5%, while C.V.'s in the other regions were between 56% and 100%. Kelp greenling were common in the SJA, SJF, and CPS regions, with C.V.'s ranging from 21% to 50%. Kelp greenling were observed at only a single station in both the SPS and HC regions, with corresponding C.V.'s of 100%.

Table 3. Minimum population estimates (in thousands of fish) and coefficients of variation for five rocky-reef species from the video survey.

	Species									
	Copper rockfish		Quillback rockfish		Black rockfish		Lingcod		Kelp greenling	
Region	# fish	%C.V.	# fish	%C.V.	# fish	%C.V.	# fish	%C.V.	# fish	%C.V.
SJA 1993	2,144.2	(35.6)	723.0	(45.1)	0	(---)	304.7	(58.4)	772.0	(27.5)
SJA 1994	3,639.5	(23.1)	1,850.1	(32.0)	28.1	(70.8)	312.7	(31.6)	576.0	(20.7)
SJF 1994	532.0	(100)	0	(---)	0	(---)	127.0	(100)	1,231.4	(49.0)
CPS 1995	109.1	(20.8)	202.1	(40.9)	5.6	(72.9)	17.6	(47.8)	25.9	(32.0)
SPS 1995	101.0	(41.9)	15.1	(66.0)	0	(---)	10.2	(45.5)	6.3	(100)
GB 1995	0	(---)	0	(---)	0	(---)	0	(---)	0	(---)
SJF 1996	100.9	(29.9)	80.8	(51.0)	433.7	(51.3)	69.9	(56.4)	362.9	(26.9)
HC 1996	86.5	(25.1)	15.8	(46.2)	0	(---)	2.0	(69.8)	1.8	(100)

Discussion

Between 1993 and 1996, more than 2,000 camera deployments were made in the nearshore (0 to –37 m MLLW) waters and shallow offshore reefs of six Puget Sound groundfish management regions. Despite attempts to eliminate non-rocky-reef habitat from the sampling frame prior to each survey, large amounts of fine grain and coarse grain sediments were sampled relative to the amount of rocky-reef habitat encountered. The amount of rocky-reef habitat was greatest in the SJA and was estimated to be about 112 km^2 (sea surface area). However, because substrate area was calculated based only on the proportion of stations containing a particular substrate type, and not on the actual station areas (which were unknown), no compensation was made for the generally larger surface areas of coarse-grain and fine-grain stations due to the shallower bottom slopes associated with these stations. As a result, the amount of rocky-reef habitat in the SJA may have been overestimated. In the future, individual stations will be digitized on the computer in order to calculate more accurate rocky-reef habitat estimates.

The amount of rocky-reef habitat in the SJF in 1994 may also have been overestimated, for the same reason cited for the SJA. As seen in Table 1, the estimate of total rocky-reef habitat in 1996 was over 60% less than in 1994. This reduction can be attributed to the change in survey design between years, which, due to the

increased sampling rate and smaller station sizes, likely resulted in more accurate substrate area estimates.

Rocky-reef habitat in the CPS, SPS, and HC regions is limited, with a combined total of only 11 km^2. Most of the habitat sampled in these regions consisted of fine grain sediments, although a considerable amount of coarse grain habitat was sampled in the CPS. Due to the large area comprised by these regions and the limited amount of sampling time available for the video surveys, it is highly likely that more rocky-reef habitat exists than was identified. For example, several popular scuba diving sites in HC are known to contain rocky-reef habitat, but were not sampled during the 1995 VAT survey. Although the size of these reefs is limited, they do appear to support localized concentrations of rocky-reef fishes, mainly rockfish and lingcod (T. Parra, WDFW, pers. Comm.). These reefs will be included in subsequent surveys of the region, but given their limited size, will likely not result in a significantly greater estimate of rocky-reef habitat.

Although the majority of the target species were observed in association with rocky-reef substrates, frequencies of occurrence were considered to be low. Depending upon the region, copper rockfish were only observed at 3% to 27% of the rocky-reef stations sampled (except in the HC). Differences in habitat quality at the rocky-reef stations may account for these relatively low encounter rates. Matthews (1989) found that densities of adult rockfishes (*Sebastes* spp.) in CPS varied between reef types and were highest on high-relief reefs. Further, we have observed that high-relief/high-complexity habitats (e.g., boulder fields) are preferred by copper and quillback rockfish. Of the rocky-reef stations we surveyed, nearly 75% were lacking in relief, complexity, or both, and less than 10% of these stations had rockfish or lingcod present. At almost half of the stations where rocky-reef substrate was dominant, the habitat consisted of low-relief and/or low-complexity bedrock reefs and walls. At the majority of stations where rocky-reef substrate was sub-dominant, the habitat consisted of sand, cobble, or gravel bottoms with widely scattered boulders. Although some of the larger boulders offered vertical relief in excess of 1.5 m, the expanse between boulders was large, resulting in low-complexity environments that generally were devoid of fish.

The relatively high frequency of occurrence of copper rockfish on artificial substrates was not surprising (Figure 2). Artificial reefs are colonized quickly by rockfish and other rocky-reef species within a few days or months of construction (Buckley and Hueckel, 1985). Shipwrecks also had concentrations of several target species. At all of the larger wrecks (>10 m length, 2+ m vertical relief), we found 20 or more rockfish present, including copper, quillback, black, and blue rockfish. Based on the results of a study conducted on a sunken dry dock in Puget Sound (Palsson and Pacunski, 1995), it is highly likely that rockfish inhabiting these sites may be permanent residents until caught in the recreational fishery.

Population estimates for the target bottomfish species were highest in the SJA and SJF regions. This result was expected given the much greater amount of rocky-reef habitat in these regions. In the other regions, where rocky-reef habitat was limited, population estimates were substantially lower. Some of our unpublished experiments have shown that the VAT camera misses up to 30% of fish in higher-complexity habitats because fish are hiding or obscured by rocks. This problem may be particularly exacerbated for lingcod, which are more difficult to detect than rockfish, due to their more camouflaged appearance. Consequently, since over 40% of fish observations occurred in higher-relief and/or higher-complexity habitats, population estimates for the target species represent minimum estimates only.

Coefficients of variation for copper rockfish and kelp greenling were relatively low in most regions, indicating that the VAT is a practical method for assessing shallow water populations of these species. Quillback rockfish, which tend to be distributed at greater depths than copper rockfish, and lingcod, which were often difficult to detect with the black-and-white camera, were less common in the VAT surveys. Consequently, C.V.'s for these species were higher and more variable than for copper rockfish, but were still within acceptable limits for a population survey. Black rockfish were seldom seen in the VAT surveys, mainly because we did not sample the very nearshore kelp beds in which this species tends to occur. As a result, C.V.'s for two of the regions where black rockfish were encountered were very high (>70%). However, more black rockfish were observed in the SJF in 1996 due to the change in survey design, which allowed for a higher rate of sampling in kelp beds, thereby reducing the C.V. to a more acceptable level.

The target species of the VAT surveys are not constrained to the shallow depths that we sampled. Copper

and quillback rockfish have been observed at depths of 140 m, and show similar habitat affinities to those we observed (Richards, 1986; Murie et al., 1993). Similarly, lingcod have been observed at depths up to 126 m utilizing complex habitats as nesting sites (O'Connell, 1993). Puget Sound reaches depths of over 100 fathoms (180 m), and it is known from WDFW trawl surveys that rockfish and lingcod inhabit these depths. Since little recreational fishing effort occurs at depths greater than 60 m, lingcod and rockfish populations at these depths may be significantly larger than in nearshore areas. Improvements to the VAT system will enable us to assess fish populations at greater depths and to characterize more habitat. A recently acquired laser scaling system will allow us to measure fish and objects in future surveys, resulting in age-structured models of the populations and better habitat characterizations. Additionally, image enhancement software will be used to aid in identifying and measuring fish from the videotapes, and should reduce the number of unidentified rockfish observed, thereby improving species population estimates. Future video surveys, especially those conducted at greater depths, may prove challenging, but should provide fishery scientists with valuable data and information concerning Puget Sound bottomfish populations and their habitat associations.

Results obtained from these and future surveys will be used to improve the management of the recreational bottomfish fishery in Puget Sound. Also, these data may be useful in defining "essential fish habitat" as required by the Magnuson-Stevens Fisheries Conservation and Management Act. Because many of the bottomfish stocks (i.e., species) in Puget Sound are characterized by the WDFW as below average or critical (Palsson et. al., 1997; West, 1997), data from these surveys may also be used to identify sites that could be incorporated into a system of "marine protected areas" for the protection and enhancement of these species.

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Dungeness Crab in the Georgia Basin: A Unique Stock!

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Abstract

Recent studies suggest that behavioral differences between Dungeness crab from the Georgia Basin and those from the outer coast effectively isolate the two stocks. The spatial distribution of Dungeness crab in the Georgia Basin is also the result of extreme environmental conditions, which largely limit high abundance of this species to areas of the basin with little thermal stratification. These data are presented to illustrate that evaluating relative species occurrence and abundance is not a trivial task, and that a broad ecological perspective is often helpful in drawing conclusions. Strictly from a Dungeness crab perspective, these data explain why Dungeness crab cycles of abundance between the basin and outer coast waters are disassociated and are relatively more stable.

Status of Puget Sound Bottomfish Stocks

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Abstract

Stock assessments were conducted for 36 bottomfish stocks in Puget Sound. Catch, effort, and survey data were assembled for the north and south Sound regions for each of 18 species or species complexes. Only 28 stocks had sufficient information to determine stock status and recent trend. The majority of these stocks were in below-average, depressed or critical abundance conditions. Thirteen of the 28 stocks were in decline while eight were increasing. The north Sound had more stocks at average or above-average conditions than the south Sound, where eight of 11 stocks were at below-average or critical conditions. The south Sound had seven stocks that lacked recent information to assess stock status.

Spiny dogfish, skates, and ratfish appeared to be in satisfactory condition. In contrast, virtually all of the codfish stocks (Pacific cod, walleye pollock, and Pacific whiting) were in depressed or critical conditions or were in decline. Rockfishes and lingcod, species living in association with rocky reefs, showed mixed patterns of stock condition. Lingcod were declining in the north and south Sound, and populations were depressed in the north Sound but were at average levels in the south Sound. Rockfish populations showed no trend in either area and were at average levels in the north Sound and at below average conditions in the south Sound. English sole and starry flounder, key flatfish stocks in the north Sound, were increasing in abundance, but the fisheries remove a substantial proportion of the adult population, which is overutilized. In the south Sound, the lack of recent fisheries precluded the determination of stock condition, but trawl survey data suggested the stocks are underutilized. A variety of species including greenlings, sculpins, and sablefish had very poor information for assessing stock condition.

PUGET SOUND RESEARCH '98

SESSION 5A

STUDYING THE NEARSHORE

Session Chair:
Ronald M. Thom
Batelle Marine Sciences Laboratory

Mapping Shorelines in Puget Sound I: A Spatially Nested Geophysical Shoreline Partitioning Model

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Introduction

The ecology of nearshore benthos (from intertidal to water depths of 10 m) has been studied in detail in many locations in the U.S., and our understanding of nearshore biological and physical processes has increased substantially. Many of the individual processes structuring nearshore communities, such as wave energy, substrate size, competition and predation have been extensively examined and are reported in the literature (Schoch, 1996). We do not know how the many processes that affect community structure interact over different scales of space and time. The complexities of these interactions may confound our understanding. However, it is clear that there are strong physical and biological linkages (Schoch and Dethier, 1996). These linkages force predictable patterns of biological communities and intertidal habitats. Determining why communities change over space and time is still a significant challenge but the patterns observed in the data can be used to predict community structure so that changes can be quantified.

Many organisms within marine ecosystems are sensitive to environmental changes or gradients and may serve as indicators of environmental health. Detecting change in biological communities is an inherent part of experimental ecological research and applied monitoring programs. Many scientists and resource agencies have attempted to monitor localized intertidal and subtidal transects in hopes of finding a short–term experimental response or a long–term indicator of ecosystem health. Long–term monitoring presumably will provide a statistical baseline from which a change can be detected. However, the dynamic nature of the marine environment causes high spatial and temporal variation in organism abundances and community structure, and generally confounds our ability to detect non–catastrophic perturbations. Biological data from intertidal monitoring stations are plagued by two fundamental problems. The first is the large temporal variability of organism abundances in natural ecosystems which masks our ability to statistically separate an actual change caused by a perturbation (the signal) from natural cycles (the noise). The second issue is a scaling problem. Extrapolating or generalizing the results of localized studies to broad areas is statistically fraught with problems. We describe here the application of a model (Shoreline Classification and Landscape Extrapolation: SCALE) that increases biological homogeneity by partitioning a shoreline into a spatially nested series of geophysically uniform segments (Schoch and Dethier, in review). By then statistically aggregating similar but spatially separated units, we can scale up localized biological data to larger regions. This knowledge is important for resolving many scientific and resource management issues in Puget Sound.

Methods

The site selected for this study was Carr Inlet (including Henderson Bay), the first major embayment south of the Tacoma Narrows in the Puget Sound estuary.

At all spatial scales the primary environmental determinants of intertidal organism abundance and community structure are substrate size (e.g., bedrock vs. gravel vs. sand etc.) and immersion time (or elevation above low water). Substrate size determines the stability (movement potential) and dynamism (movement frequency), both factors in community disturbance. Solid surfaces generally preclude infauna, while dynamic mobile substrates preclude most sessile organisms. Many mobile but low dynamism substrates (e.g., mud) are extremely rich in biota, especially infauna. Sediment size and dynamism also affect moisture retention, O_2 content, and organic content. The position or

elevation within the intertidal zone leads to differences in immersion times, which result in distinctive community zonation patterns.

Another key physical feature is wave energy, which affects community structure both directly through episodic disturbance events and indirectly by controlling substrate dynamics over short and long temporal periods. The magnitude of wave runup or swash can also affect community structure by elevating zonation levels, delivering nutrients and preventing desiccation. In relatively protected areas such as Carr Inlet, wave runup is practically non-existent and large waves are infrequent, such that wave energy does little to directly structure the intertidal community. However, indirect effects include current propagation and substrate movement over long temporal scales. In Carr Inlet, the processes of sediment suspension and transport can be expected to occur primarily during the winter when strong southerly winds blow along the axis of the bay.

Partitioning within Carr Inlet of 1–10 km long shoreline blocks was based on gradients of salinity and water temperature, and the location of major sediment plumes. Night-time imagery from the Advanced Very High Resolution Radiometer (AVHRR) satellite sensor (band 4, 1 km resolution obtained from the National Environmental Satellite Data and Information Service) provided a large scale temporal data series of sea surface temperature (SST). These data showed a consistent (over a three-year annual interval) temperature gradient from the cold deeper water in outer Carr Inlet to the warmer shallow water of inner Henderson Bay. LandSat 5 data from bands 1, 2, and 3 were used to locate sediment plumes, areas of urban, suburban, timber, and agricultural development, and for measuring wave fetch at scales of 1–10 km. The only significant sediment plume identified emanates from Burley Lagoon and flows along the eastern shoreline. Field measurements of sea surface temperature and conductivity near the shore were made over a two–day period with a hand held instrument at 14 sites, spaced approximately five km apart. Salinity was calculated from these measurements.

The above 10-km blocks or quadrants of Carr Inlet were partitioned into 100–1,000 m preliminary segments based on photogrammetric analyses of the principal shoreline geomorphology. The shore type was classified according to a system used for resource management in British Colombia (Howes et al., 1994). Low altitude color infrared (CIR) aerial photographs (1:13,000 scale), flown at an extreme low tide, were used to differentiate well drained or coarse substrates (high radiance) such as pebbles and cobbles from saturated or fine substrates with high moisture content (low radiance) such as silt and sand. The CIR photography was also used to delineate the intertidal zone from the uplands using the strong chlorophyll signature of terrestrial plants. The lower intertidal boundary was also shown clearly due to the dark body properties of water at infrared wavelengths. The digitized intertidal zone map was used in a GIS to calculate areas and dimensions of shore partitions.

The geomorphic shore segments described above were then refined by ground surveys to further partition the shoreline, in both the alongshore and across–shore, according to beach slope and substrate sizes (primary, secondary, and interstitial). Geophysically homogeneous alongshore segments (10–100 meters in length) were identified in the field and delineated on orthophoto basemaps during the spring low tides from April 8–11, 1997. Each alongshore segment was vertically separated into four across–shore polygons centered at specific elevations that correspond to immersion times during the daily tidal cycle, based on the mean tidal statistics for Carr Inlet.

Table 1 lists the attributes and spatial scales used for shoreline segmentation. Substrate size was measured according to the Wentworth particle size classification for the following percent cover categories: primary (for particles comprising more than 60% of the substrate), secondary (for particles less than 40% of the substrate), and interstitial. Beach slope was measured with a hand held digital inclinometer. Substrate permeability and groundwater salinity were measured in the lower intertidal zone by digging a hole to 0.3 m and inserting a perforated bucket. Permeability was quantified by the time required to fill the bucket with ground water, and salinity was measured *in situ*. Substrate roughness was qualitatively categorized based on the degree of armoring. Groundwater seepage was estimated as a percentage of the polygon length exhibiting seepage from the beach prism based on photogrammetric interpretation of CIR aerial photos. Dynamism is the

relative bed stability calculated using predicted wave velocities. The effect of waves on beaches is best represented by surf characteristics. The Iribarren number was calculated for each across–shore polygon since slope angles vary considerably across most segments: an upper intertidal seawall is generally highly reflective and a lower intertidal sand flat is highly dissipative.

Table 1. Geophysical attributes of the SCALE shoreline partitioning model.

Qualitative	Quantitative (except where noted)			
Shoreline Type (100–1,000 m)	Block (1–10 km)	Segment (10–100 m)	Polygon intertidal zone	
substrate size	salinity	aspect	surf parameter	(calculated)
slope angle	surface temperature	drift exposure	slope	
geomorphological form	average fetch	wave energy	dynamism	(calculated)
			roughness	(qualitative)
			substrate size:	
				primary grains
				secondary grains
				interstitial grains
			permeability	
			seepage	(qualitative)

There are few published wave statistics for this area, so for each segment we derived the required parameters from measurements of maximum fetch, or the longest overwater distance unimpeded by a landmass (obtained from a GIS coverage of the South Sound). We classified each distance measurement and estimated the wave statistics for each fetch class (Table 2) from graphs published in the Shore Protection Manual (CERC, 1984).

Segment polygons for each intertidal level were aggregated separately using a combination of multivariate hierarchical agglomerative clustering and sorting to produce relatively similar groups. The large number of segments (310 in about 56 km of shoreline) in the project area was an indicator of local shoreline heterogeneity, most of which was explained by differences in wave energy (surf similarity) and substrate particle size (primary and secondary). These variables and dynamism (substrate stability) were assumed the most important, or primary, determinants of community structure. The remaining variables, considered of secondary importance, include permeability and roughness (which co–vary with particle size), interstitial particle size and groundwater seepage. The primary variables were given more weight by separately clustering the secondary variables and then adding the resulting secondary group variable to the smaller matrix of primary variables. Each matrix was relativized by column maximum values to equalize the various measurement scales, then clustered using Sorenson's city block distance and the centroid linkage method. The centroid method was selected for providing the best separation of clusters, but since it is space–contracting, there is a chance that polygons may become part of a growing cluster when they should have formed the nucleus of a new cluster. An alternative would be to use a space–conserving method such as the group mean linkage, but results from preliminary trials produced a large number of small clusters with few natural groupings. We used Wishart's objective function (1969) to evaluate the amount of information lost at each step of aggregation. The dendrograms showed that 95% of the segments were clustered before 25% of the information was lost according to this evaluation function. Using Wishart's 25% as the clustering cutoff, 20 groups were selected for the secondary group cutoff and 12 for the primary grouping. Primary cluster group membership was evaluated using direct discriminant function analysis to determine the probability of correct classification for each across–shore polygon.

Table 2. Wave parameters derived for calculating the surf similarity index.

Fetch Distance (km) (CERC)	Sustained Wind Speed (kts) (CERC)	Significant Wave Height (m) (CERC)	Wave Period (s) (CERC)	Wave Length (m)		Energy Category (SCALE)
<0.1	5	0.1	1	1	1	sheltered
0.1–0.5	10	0.2	1.5	2	2	
0.5–1	10	0.3	2	6	3	protected
1–5	20	0.4	2.5	10	4	
5–10	20	0.5	3	14	5	semi–protected
10–50	30	1	4	25	6	
50–100	30	2	5	40	7	semi–exposed
100–500	40	3	6	60	8	
500–1000	40	4	8	100	9	exposed
>1000	50	5	10	150	10	

Results

Based on the results of the AVHRR data analysis, the field measurements of SST, salinity, and measurements of wind fetch, Carr Inlet was subdivided into four spatial blocks (quadrants) to reduce the effects of these gradients. Block extent was visually determined from GIS overlays of these data. While these gradients undoubtedly vary seasonally, the AVHRR imagery showed spring and summer trends for SST that were sufficiently consistent from year to year (May 1995–May 1997) to justify spatial blocking.

Photogrammetric segmentation by shore type generated 23 partitions, with three principal substrate types represented (mud, sand, and gravel). Mud shores were typically low angle and sheltered, with a low radiance signature indicating relative impermeability. Sand beaches had a higher radiance with a smooth texture and often showed well developed bars and troughs over the low tide terraces. The "gravel" substrate is a complex and highly variable mix of small boulders and cobbles overlying gravel, sand, and mud, with occasional areas of hardpan (consolidated clays). These show as high radiance textured features on the CIR imagery. Generally the beaches in the project area are vertically complex with the upper zone substrate being different from the middle and lower zones. Characterization at this spatial scale was based on the substrate type with the largest surface area for a given segment.

The ground surveys delineated 310 alongshore segments, composed of 1227 across–shore polygons (309 upper, 304 upper–middle, 313 lower–middle, 301 lower: "missing" polygons occurred, for example, in the shallow inlets where there was no low zone). The cluster analysis forced each across–shore polygon into one of 12 groups (12 clusters for each of three zones). Figure 1 shows the distribution of segment clusters in terms of the number of segments per cluster and the percent of shoreline length represented by each group. Spatially dominant habitats in the upper–middle zone are the clusters 1 (semi–protected pebbles), and 2 (protected sand and pebbles), representing 60% of the project shoreline. The lower–middle zone has three spatially dominant clusters (1 is protected pebbles, cobbles and sand; 2 is protected pebbles and cobbles; and 3 is protected pebbles), representing 64% of the shoreline length. The lower zone habitats are somewhat more evenly distributed, but four clusters still dominate (cluster 3 is semi–protected sand; 4 is protected sand and silt; 5 is protected sand, pebbles, and mud, and cluster 8 is mostly sheltered silt) with 58% of the shore length.

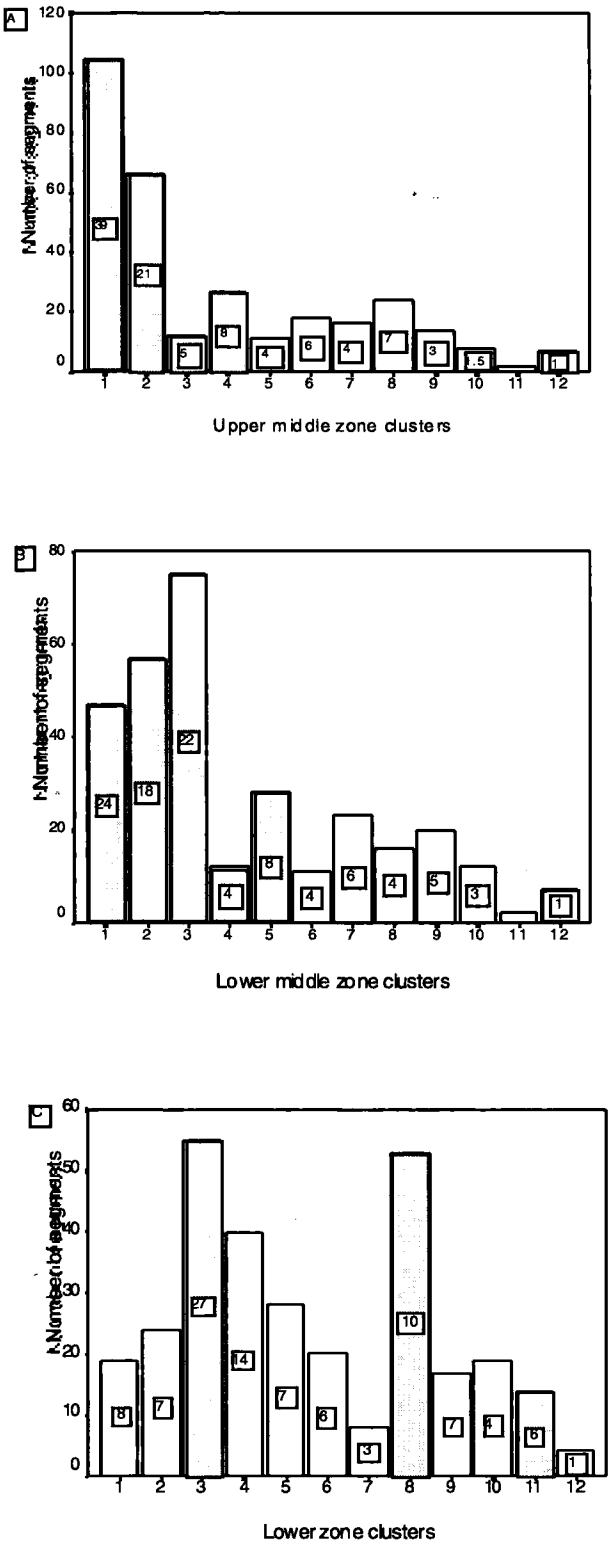

Figure 1. Distribution of intertidal habitat types represented by clusters of shoreline segments. The height of each bar represents the number of segment members for each cluster and the number inset on the bar is the percent of shoreline length represented by each. The shaded bars are those clusters where biota were sampled from a random selection of segments.

The cluster membership identifier and the spatial block designator were added to the geophysical data matrix, and the database was sorted resulting in subgroups of polygons nested within each spatial block. The biological sampling design was centered around these analysis groups (Figure 2; see Dethier and Schoch, this volume). The subset of cluster segment members within a spatial block are referred to by the most general classification category of either mud, sand, or gravel shoreline types. In most cases the polygon substrate is considerably more complex. For example, the upper–middle and lower–middle zones for both the "sand" and "gravel" shoreline segments were characterized by cobbles and pebbles, usually with interstitial sand or with underlying hardpan. Because exact physical matches for all zones among segments were unlikely, priority was given to matching the lower zones (there is some variation within groups in substrate type and seepage, especially in the middle zones for the mud and sand groups).

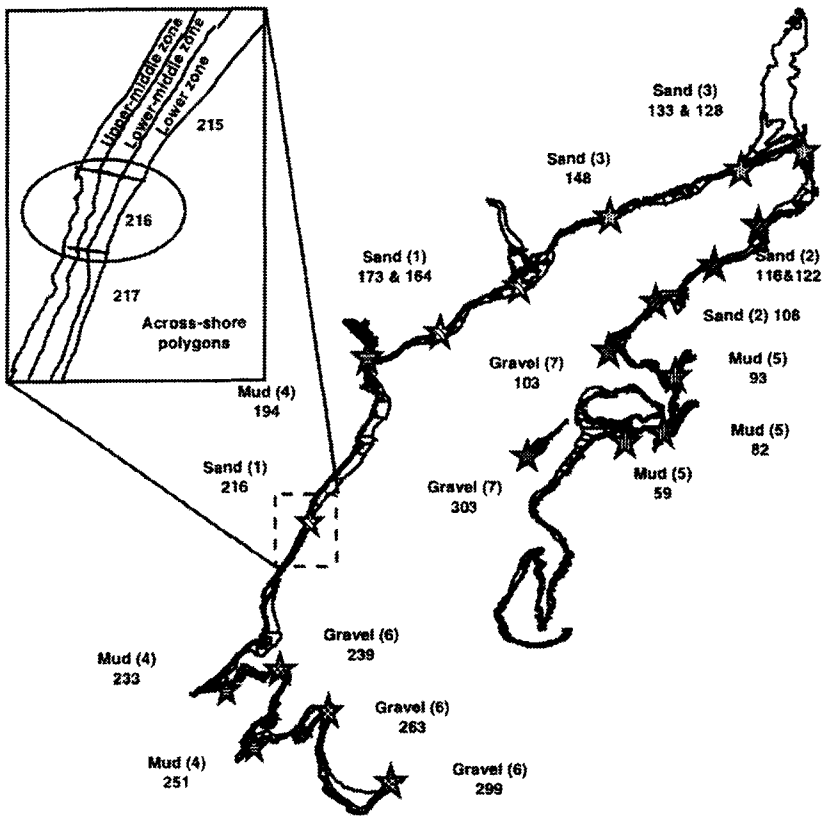

Figure 2. Map of the Carr Inlet intertidal zone (part of a GIS database) illustrating the spatial distribution of the shore polygons. Detailed partitioning is shown for Segments 215–217 in the enlarged inset. The stars show the locations and numbers of shore segments randomly selected for biotic sampling, the analysis group number in parentheses, and the general shore type.

Conclusions

Our ability to evaluate the scale and consequences of changes in the ocean's biodiversity due to human activities is seriously compromised by critically inadequate knowledge of the patterns and the basic processes that control the diversity of life in the sea. Studies applied to the nearshore are helping to define the patterns and the processes influencing marine biodiversity. If the biogeochemical processes determining patterns in nearshore habitats can be defined as proposed by

this study, then predictions can be made about community structure over many scales of space and time. This model has application to oil spill damage assessments, inventory and monitoring programs, global change, and biodiversity studies. Additional applications can be explored in hindcasting the ecological functions of disturbed habitats for mitigation and restoration projects, in forecasting impacts based on trends in human or natural perturbation patterns, and in site selection for experiments in community ecology.

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Mapping Shorelines in Puget Sound II: Linking Biota with Physical Habitats

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Introduction

Stresses on marine ecosystems due to changing global climate and the encroachment of human development are manifested in the Pacific Northwest by loss of habitat and the reduction or extinction of many important organisms. Studying the ecological functions of marine habitats and measuring the extent and rate of habitat loss is important for determining the 'health' of Puget Sound. To monitor habitat changes in Puget Sound, we need to map shoreline types and inventory the marine biota, e.g., for: 1) measuring change due to natural or human-caused perturbations; 2) mapping areas with key resources, or potential for these (e.g., the right substrate and depth for eelgrass); and 3) choosing sites for research and for monitoring programs. Our ability to detect change in the biota of the Sound requires that the information we gather about the biota has a sufficiently fine spatial scale of resolution, and that we take steps to minimize the inherent variability that exists in all ecological data sets. One way to do both is to take into account the geophysical features of the shorelines being mapped or studied, since such features (e.g., wave energy, substrate type, salinity) strongly affect biotic communities.

Schoch and Dethier (these proceedings and in review) describe a model (SCALE) for partitioning and classifying shorelines such that geophysical homogeneity within a beach segment is maximized. Here we describe to what extent this process leads to biotic homogeneity. How closely are the biota of the intertidal zone in Carr Inlet tied to their physical habitat types, i.e., to a particular combination of substrate, salinity, wave energy, etc.? How similar do physical habitats have to be before one can expect to see parallel communities in them? To what extent can we extrapolate the character of biotic communities from one beach to another?

Methods

The biota of intertidal beaches in Carr Inlet were sampled during springtime low tides in May, 1997. Data were taken at three sand, three mud and three gravel beach segments in each of three zones (at 0, 1.5, and 3 m above mean lower low water [MLLW]), and additional data were taken at six sand, three mud, and two gravel segments in the lower zone only. Sampled segments were selected randomly from the geophysical groups described in Schoch and Dethier (this volume) after accounting for spatial blocking. At each sampled level, a 50-m horizontal transect was positioned near the center of the segment to eliminate edge effects. Ten random samples were collected along each transect, with two in each of five 10m-long sections (to evaluate within-transect homogeneity). Each sample consisted of quantifying epiflora and fauna in a 0.25-m^2 quadrat, and infauna in a 10-cm diameter core dug to a depth of 15 cm. Core samples were sieved on 2-mm mesh. Several samples from each substrate type were also sieved to 1 mm, but few additional organisms were retained. All organisms not identifiable in the field were placed in formalin and later identified in the lab, when possible to the species level.

The sampling design thus had four nested spatial scales for each shore type: samples (quadrats and cores) within each transect section (meters apart); transect sections within each segment (tens of meters apart); segment within a geophysical group (kilometers apart); and groups within the inlet (among spatial blocks: tens of kilometers apart). Our predictions, based on the SCALE model, were:

1. Within a beach segment (i.e., among the five sections of the transect line) there should be high biotic uniformity—since beach segments were defined by being geophysically homogeneous, the biota were predicted to be homogeneous, too.
2. Among beach segments that clustered together within a block, i.e., sediments that were all fairly similar geophysically, the biota should again be similar.
3. Among beach segments in different blocks, i.e., those varying more in wave energy and salinity but still very similar in substrate type, we expected more biotic variability.
4. Among segments that did not cluster together, i.e., those with different substrate types, we expected very high biotic variability.

Multivariate techniques were used to detect patterns in the communities across spatial scales. Data matrices of abundances of each species were transformed to reduce the beta diversity, skewness, and coefficients of variation for column (species) and row (sample unit) sums. For the multivariate analyses, species with a frequency of occurrence of <5% were deleted. Two transformations were then applied independently, one that retained abundance information and the other derived from presence/absence data. The first was a double relativization, first by species maximum and then by sample unit totals. This equalized the data, reduced the effect of rare and abundant species, and allowed both percent cover of sessile species and counts of mobile species to be considered together. The second transformation applied the Beals smoothing function to reduce the effects of correlations among zero-rich data (Beals, 1984). The effects of these transformations were evaluated by calculating descriptive statistics for each matrix before and after transformation. The Beals transformed matrices were generally the best at evaluating differences among communities when their composition was very heterogeneous, for example, when comparing all substrate types or all levels. But as community composition became more homogeneous, for example within a given level and substrate type, then evaluations based on the abundance matrices were more sensitive because more information was retained. Most results presented below thus involve the abundance matrices.

The transformed data sets were ordinated using non-metric multidimensional scaling (NMS) to evaluate how each performed in describing the differences in community structure among the groups of sample units. Graphical plots of ordination results for the two axes explaining the greatest proportion of the variance were examined together with overlays of the various grouping variables (the different spatial units). Formal significance tests for differences among groups, either in species abundances or species presence/absence, were computed using a non-parametric multi-response permutation procedure (MRPP, Zimmerman et al., 1985). This was used to test the null hypothesis that two or more groups occupy the same region in species ordination space. MRPP has the advantage of not requiring assumptions such as multivariate normality and homogeneity of variances. We evaluated the relative homogeneity of communities within and among clusters of beach segments by calculating the departure (the value R) from perfect within-group homogeneity (Berry et al., 1983).

For each species at each spatial scale we also calculated an 'indicator value' (Dufrene and Legendre, 1997) which integrates the "reliability" or fidelity of each species to its habitat. This value combines information on the evenness of species abundances in a particular group of samples and the fidelity or faithfulness of occurrence (frequency) of a species in that group.

Finally, we used ANOVAs to test which organisms showed low spatial variability at different spatial scales, thus determining the species whose abundances could be extrapolated from segment-level spatial scales to larger areas.

Results and Discussion

A total of 840 quadrats and cores were collected, containing a total richness of 114 taxa. We found 98 of the 114 taxa in the lower zone, 49 in the middle, and 21 in the upper. The sand habitats had 113 taxa, while the gravel had 94 and the mud had 58. Biota among substrate types differed especially clearly in the low zone. Low zone sand segments were either dominated by the sand dollar *Dendraster* (reaching densities of

>1000/m^2) and had few other infauna, or had no *Dendraster* and a diverse infauna of burrowing sea cucumbers, anemones, and tube-building and mobile polychaetes. Low gravel segments were characterized by barnacles and ephemeral green algae on the surface, and by extremely numerous capitellid polychaetes in the sediment, often with a variety of predatory worms such as nemerteans, glycerids, goniadids, and hesionids. Low mud segments were dominated by ghost shrimp and associated commensal fauna, such as small clams and crabs that inhabit shrimp burrows, and by capitellid and predatory polychaetes. Ephemeral green algae, opisthobranch molluscs, and shore crabs were found on the surface in many segments.

The multivariate analyses of whole communities, as illustrated by the sample ordinations in Figure 1, fairly closely followed our predictions about levels of biotic homogeneity with spatial scale. The unexpected result was just how sensitive the biota were to seemingly subtle changes in geophysical features. The NMS plots in Figure 1 can be interpreted most straightforwardly by recognizing that 1) each point is a sample unit (quadrat + core), and 2) the closer together the points lie in the two-dimensional space plotted, the more similar the communities are (in identities and abundances of species).

Plots A, D, and G show the variability within a segment for each of the three substrate types in the low zone. These points are rather highly scattered within these geophysically homogeneous segments, and R values (measuring group homogeneity) were variable (.101, .030, and 0, respectively). However, this is largely a scaling issue. On a scale of 10s of meters, the beach segment (the whole 50-m transect) was classified as geophysically uniform. But our samples, especially the cores, were very small; thus they often hit little patches with different grain size, or a spot strongly affected by the presence of one ghost shrimp or large clam, so they showed fine-scale patchiness.

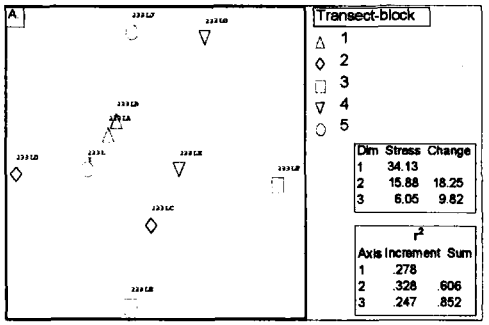
However, this apparent heterogeneity is put into better perspective when examining the scale of several beach segments within one block, in plots B, E, and H. Here the points that looked scattered on the first set of plots show quite high uniformity—e.g., all the symbols from segment 233 now cluster together well. So from a larger spatial scale, we find that the biota of each beach looks fairly uniform. This consistent within-segment homogeneity relative to among-segment heterogeneity suggests that the partitioning model was successful in reducing geophysical gradients that cause ecological heterogeneity at the scale of interest. R-values were higher at this spatial scale for each substrate type (.120, .130, .102) than at any other scale.

However, these plots also show that there is still a moderate amount of variability in biota among beaches that clustered together. For all three substrate types, there was some fidelity of a particular community to its own beach. Some of this variability can be explained by subtle physical differences among beaches, and by the effects of these differences on the fauna. For example, in the mud (plot B), segment 194 had higher concentrations of sub-surface sand than the other two segments, and it was the only mud segment that was dominated by *Dendraster*. *Dendraster* strongly affects other species in a beach segment through bioturbation; at high tide, the sand dollars move to the surface of the substrate and suspension-feed, whereas at low tide they bury 5–10 cm below the sediment surface, digging up other organisms in the process. Thus the presence of sand dollars, which prefer sandy sediments, caused the points of segment 194 to cluster separately from the more muddy segments. Likewise in the sand (plot E), segment 173 had very few sand dollars, apparently because of a freshwater seep that made the low zone uninhabitable for them. Thus the points for that segment are separated from the other low sand segments in this group, where freshwater was not a problem.

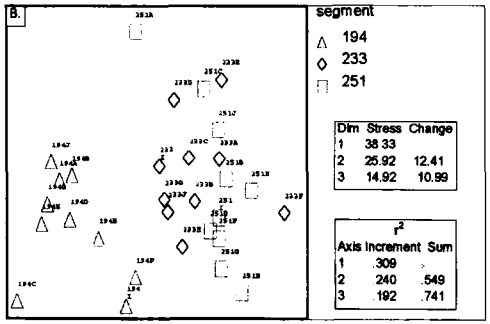
The last column of plots (C, F, and I) compares the biotic similarity among blocks, or different regions of the inlet (e.g., for the mud, the triangles were from the SW quadrant of Carr, while the diamonds were from the SE quadrant). There is further-reduced biotic homogeneity at this scale, as shown by the scatter of points and by the R values (0.095, 0.097, 0.038), which were lower than at the within-block scale. In the same way that some species showed fidelity to particular beach segments at the group level, here some species were found in only one block. For example, the burrowing anemone *Edwardsia* was found only in sand group 3, in the warmer, less saline corner of Carr Inlet.

Again, it is important to note that segments that appeared scattered at smaller spatial scales now look quite clumped; with a broader view, the different beaches within a block really have quite similar

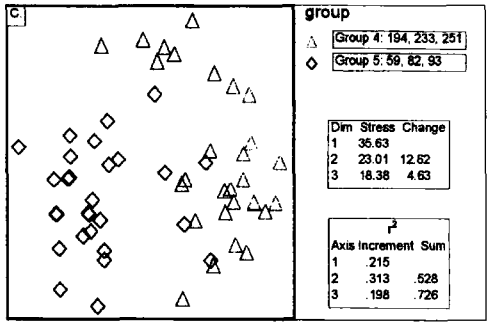
Lower mud transect-block comparisons in Segment 233



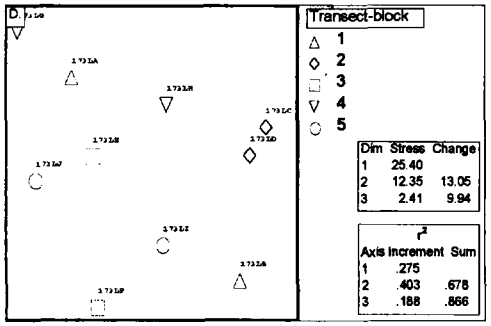
Lower mud segment comparisons in Group 4, Block 4



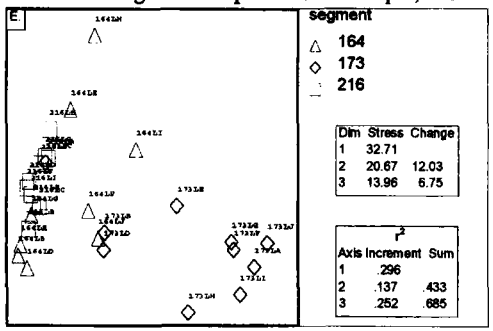
Lower mud group comparisons



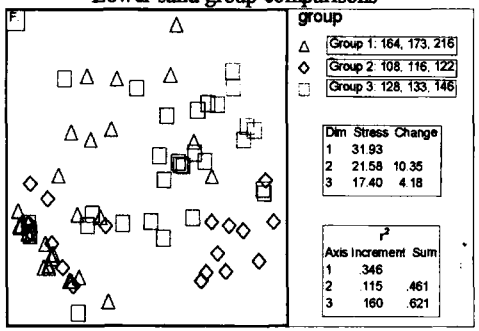
Lower sand transect-block comparisons in Segment 173



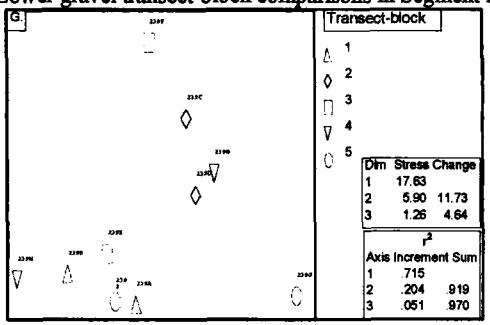
Lower sand segment comparisons in Group 1, Block 4



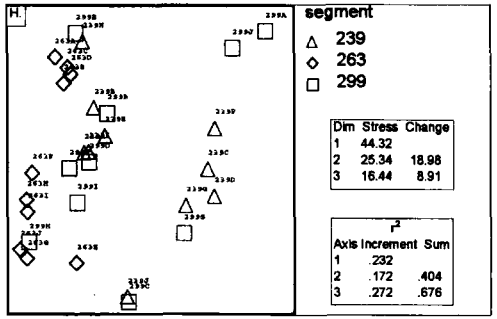
Lower sand group comparisons



Lower gravel transect-block comparisons in Segment 239



Lower gravel segment comparisons in Group 6, Block 4



Lower gravel group comparisons

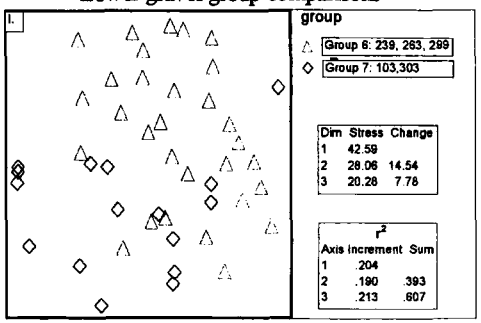


Figure 1. NMS ordinations of samples in species space.

biota. This shows that our view of biotic similarity is completely dependent on the spatial scale being examined; if we were comparing these mud segments with some mud biota from Southern California, the points from Carr Inlet would cluster very tightly relative to the California samples. An issue that requires further testing is how similar biotically these regions of Carr Inlet are with similar habitats elsewhere in South Sound, and elsewhere in Washington.

Figure 2 illustrates how different the communities were at each spatial scale. Low T values indicate very little difference among groups of samples at that scale, or relatively small distances among groups of points in the previous graphs. At the segment scale, with maximum geophysical homogeneity, differences among transect sections within each segment (e.g., among the three segments in mud group 4) were very small. At the block scale, differences among segments were larger, but still fairly small. Differences among blocks (i.e., sides of the inlet) were still larger, and the last point indicates very large differences among all substrate types in the low zone. So there was, as would be expected, very little community similarity among shore types (or a very large separation among points), and a steady increase in similarity as one examines beaches that are more and more alike geophysically.

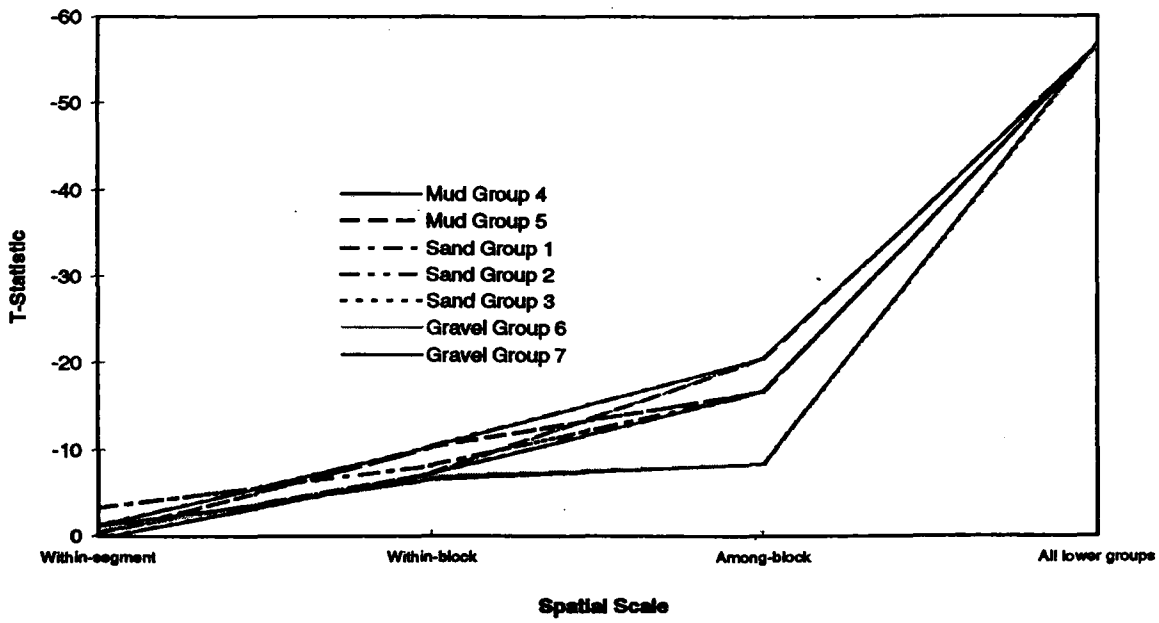
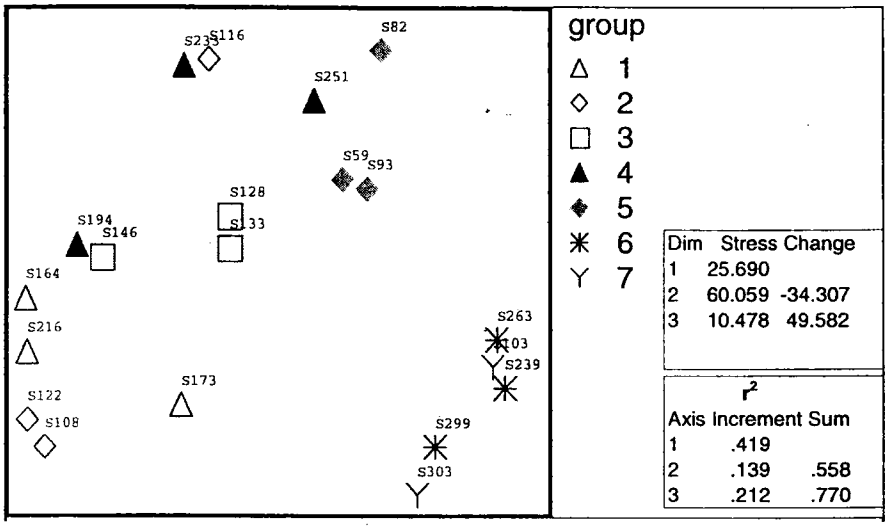


Figure 2. Differences in multivariate separation among low intertidal community groups at increasing spatial scales. Small T values indicate very little separation among the communities being compared.

The calculated 'indicator values' allowed an assessment of species that could be considered characteristic of a particular set of geophysical conditions, i.e., ones that tended to be found with high fidelity in a group of samples. Figure 3 lists some of these species for each substrate type in the low zone, and shows an NMS plot of how, using only the indicator species, groups of similar segments tend to cluster together (Groups 1, 2, and 3 are sand; 4 and 5 are mud; and 6 and 7 are gravel). Gravel groups had their patterns driven especially by the epifaunal *Balanus glandula* and *Enteromorpha*, and the infaunal polychaetes *Micropodarke* and *Notomastus tenuis*. One gravel group (in a slightly higher-energy area) was distinct from another by having *Acrosiphonia, Crepidula, Ophiodromus*, and Piddock clams. Two of the mud groups were separated from the rest by abundant populations of *Callianassa, Goniada*, and *Tellina*. All three sand groups shared nemerteans (not common, but present in all groups), *Punctaria, Spiochaetoperus*, and ulvoids, but only Groups 1 and 2 had significant populations of *Dendraster* and *Scoloplos*, and only Group 3 (warmer, lower salinity) had *Edwardsia, Haminoea* eggs, and *Notomastus lineatus*.



Lower Zone Indicator Species

Organism	Sample	Axis 1	Axis 3
Balanus glandula	quadrat	(+) 0.487	(-) 0.082
Callianassa californiensis	core	(+) 0.005	(+) 0.262
Callianassa californiensis	Quadrat	(-) 0.019	(+) 0.406
Crepidula sp.	Quadrat	(+) 0.279	(-) 0.058
Dendraster excentricus	Quadrat	(-) 0.520	(-) 0.177
Enteromorpha sp.	Quadrat	(+) 0.490	(-) 0.109
Eupolymnia heterobranchia	core	(+) 0.000	(+) 0.255
Goniada annulata	core	(+) 0.262	(+) 0.084
Gracilaria sjoestedtii	Quadrat	(-) 0.016	(+) 0.287
Haminoea vesicula	core	(-) 0.007	(+) 0.369
Hemigrapsus oregonensis	Quadrat	(+) 0.379	(-) 0.001
Unidentified red crust	Quadrat	(+) 0.270	(-) 0.080
Macoma juv.	core	(+) 0.003	(-) 0.253
Micropodarke dubia	core	(+) 0.287	(-) 0.237
Notomastus tenuis	core	(+) 0.352	(-) 0.186
Tellina sp.	core	(+) 0.001	(+) 0.397
Ulva sp.	quadrat	(-) 0.365	(+) 0.010
Total = 17			

Figure 3. NMS plot of lower zone indicator species. The axis values give the r^2 values correlating each species to the tow illustrated axes on the NMS plot.

Once we found these indicator species, we ran more analyses on them to discover at what spatial scale each became variable—i.e., some species might predictably be present at segments within one block, but not in a different block. These data can be used to help pick out taxa that would be best at detecting change at various scales. For example, the burrowing anemone that was very characteristic of the low-salinity warm-water corner of Carr Inlet but was absent elsewhere would be a poor choice of taxa for monitoring on an inlet-wide scale. Others, like the clam *Tellina* in the mud, were predictably found in most beach segments of that type in the whole inlet, and could make a good taxon for comparison with other regions because of its low variability in this one.

Conclusions

1. It is possible to partition and classify intertidal shorelines such that geophysical heterogeneity is minimized within a given segment of the shore, and with this geophysical homogeneity comes

biological homogeneity. For Carr Inlet, we can predict with reasonable accuracy what organisms should be present in beaches that we did not sample.

2. Looking at broad-scale patterns in biota of shorelines will always entail accepting much inherent variability, because the biota shifts in character with fairly subtle changes in physical characteristics.
3. This methodology should be able to provide a relatively low cost, low-tech, high-resolution way to quantify the state of Puget Sound shoreline habitats as they are today.
4. Since the biota vary among locations, even when the locations are all relatively pristine, we need this kind of high-resolution data for the Sound if we are ever going to be able to assess health or detect change through time.
5. This methodology should also be useful for comparing communities in clearly degraded areas with geophysically similar but relatively pristine ones.
6. More field work is needed to determine how much variability in biota is added at increasingly large spatial scales.

Acknowledgments

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Mapping Shorelines in Puget Sound III: Management Applications for Inventory and Monitoring

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Introduction

Nearshore habitat degradation and loss are recognized to be major threats to the health of Puget Sound (British Columbia/Washington Marine Science Panel, 1994). Inventory data is needed to characterize the quantity, location, and quality of habitats, and to guide land use planning. Information on trends in habitat health is needed to identify the habitat features and functions that are most at risk, and to relate these changes to the state of the Puget Sound ecosystem.

The Nearshore Habitat component of the Puget Sound Ambient Monitoring Program (PSAMP) has the dual goals of inventorying nearshore habitat and monitoring trends in health. For the purpose of the monitoring program, nearshore habitat includes the physical and biotic components of intertidal and shallow subtidal areas. Monitoring habitat is a challenge due to the size and complexity of the study area, which includes approximately 2,400 miles of shoreline east of Cape Flattery, and encompasses a wide range of habitats, from vertical rocky shores to wide, protected mudflats. Human activities range from intensive in the highly industrial urban embayments to relatively minor in the least developed areas.

The Nearshore Habitat Program inventories nearshore vegetation by collecting and classifying multispectral sensor data, and inventories other shoreline characteristics using field surveys in conjunction with photo interpretation. At current funding levels, Sound-wide mapping will be completed within 15–20 years. A PSAMP review in 1995 recommended examining alternative methods to map resources Sound-wide in less than five years (Shen, 1995). Additionally, it recommended initiating a program to monitor trends in nearshore habitat health. This paper responds to the recommendations. It reviews user needs, how current systems fulfill user needs, and how inventory methods are being changed in response. It then reviews results of research that tested the feasibility of using a linked geophysical mapping and biota sampling model for inventory and monitoring called SCALE (Shoreline Classification and Landscape Extrapolation).

User Needs

Inventory Information Needs

The Nearshore Program identified two general uses of habitat information, based on information requests: summary resource information for decision making and data for analysis. Summary information needs to address regulations regarding tidal areas, and to be accessible to non-specialists. Commonly, summary information is needed for a specific area of interest to support a permitting or planning decision by a planner, habitat manager, lease manager, or permit reviewer. Information is needed on intertidal zone location, landform type, substrate type, and vegetation present, along with information about critical areas utilized by valued or protected species. According to the Habitat Loss Work Group findings, Sound-wide coverage is needed in a relatively rapid time frame and polygon-based mapping is preferred, similar in format to the now outdated Coastal Zone Atlas (Washington Nearshore Habitat Loss Work Group, 1998).

Summary information needs to be in paper format because many users lack the hardware, software, expertise, or time to use a Geographical Information System (GIS). Many resource managers are unable to use digital data, including those at the Department of Natural Resources and the Washington Department of Fish and Wildlife. Similar experiences have been reported at the local level. The Washington Sea Grant Program found that 83% of local planners do not have the capability to display GIS maps (Goodwin, 1997). Paper map production would increase data distribution costs significantly.

Another set of users needs data with higher spatial resolution and more precise classification categories. Their projects analyze habitat abundance, distribution, quality, and suitability for different species of interest. Digital information is required for area calculation and integration with other data sets. Examples of information requests that we currently receive and we feel detailed mapping would address, include:

- Landscape- or watershed-scale shoreline planning at the local and state level, and review of these plans;
- Habitat assessment modeling in restoration projects. Current examples of projects that could utilize detailed mapping include the habitat analysis projects in Commencement Bay and the Nisqually Wildlife Refuge;
- Oil spill response and damage assessment or other disaster management;
- Analysis of proposed large-scale developments, such as the proposed Cherry Point industrial park, or the Army Corps of Engineers Lummi Road Dike Project;
- Identification of invertebrate and vegetation communities that support food-web interactions or reflect pristine or degraded conditions;
- Comparison of degraded sites to nearby un-impacted areas;
- Identification of resource-rich areas for preservation; and
- Identification of potential habitat for species of interest.

Trends Monitoring Needs

The general goal of long-term monitoring is to provide a statistical baseline from which change can be detected. However, the dynamic nature of the marine environment causes high spatial and temporal variation in organism abundance and community structure. Two common problems arise. First, many monitoring and impact detection programs have confounded spatial and temporal variation by assuming that change has occurred at an impacted site because it is different from a control site, when really the sites were not adequately matched (Schmitt and Osenberg, 1996). Second, results often need to be generalized from specific sites to a large area.

The PSAMP Management Committee has outlined basic requirements for its monitoring programs. Monitoring must measure valued ecosystem components in a cost-effective manner, be meaningful to the public, and link to management activities. The conceptual model of Puget Sound identifies broad questions about habitat to be addressed (Redman, 1996):

- How is the condition of Puget Sound biota correlated with environmental or food web stresses? Biotic habitats of special concern include marine vegetation such as kelp and eelgrass beds and biotic communities that support valued or protected species.
- How is the quantity and quality of the ambient physical environment correlated with Puget Sound's biological communities and functions? Priority issues include the effect of shoreline alteration and changes in water quality on habitats and the species they support.

Inventory and Monitoring Systems

Current Inventory Systems

Two shoreline classification systems are currently used in Puget Sound for general-purpose shoreline inventory. "A Marine and Estuarine Classification System for Washington State" (Dethier, 1990) is used by the Nearshore Habitat Program in the Department of Natural Resources. The Washington Department of Fish and Wildlife uses "The British Columbia Shore-Zone Mapping System" for oil spill response planning (Harper et al., 1991; Howes, 1994).

A Marine and Estuarine Classification System for Washington State is based on the National Wetlands Inventory (Cowardin et al., 1979), with modifications specific to marine and estuarine areas. Data is collected in the field on aerial photographs, then overlayed onto orthophotographs and digitized. Final information includes polygons representing marine or estuarine region, wave/current energy, intertidal or backshore elevation, and substrate type. Substrate information is the most detailed. The minimum mapping unit is approximately 0.5 acres. For a description of methods see Berry and Ritter (1997).

The Nearshore Habitat Program maps nearshore vegetation types by classifying multispectral sensor data. Eight nearshore vegetation types are included: eelgrass, kelp, salt marsh, green algae, red algae, brown algae, mixed algae, and spit/berm vegetation. Resolution is 4 meters. For a description of methods see Berry and Ritter (1997).

Using current methods, the Nearshore Habitat Program could map all intertidal areas in Puget Sound in 15–20 years. Users have indicated that this schedule is not rapid enough, and have recommended examining alternative systems (Washington Nearshore Habitat Loss Workgroup, 1998).

The British Columbia Shore-Zone Mapping System was designed to summarize coastal features for oil spill response planning. The system describes a variety of shoreline characteristics including substrate type, landform, shoreline type, and vegetation. The BC Shore-Zone Mapping System differs from The Marine and Estuarine System primarily in its data format. Rather than delineating polygons, a line is drawn along the shoreline and data tables containing information are attached to segments of the line. The line-based data format produces imprecise area calculations, and is harder to use. However, the collection system is much more rapid. With current funding, the Nearshore Habitat Program could complete Sound-wide mapping in approximately five years.

We are currently evaluating inventory information created using the BC Shore-Zone Mapping System. We are also working with state and local representatives and the Habitat Loss Workgroup to see if the data fulfills user needs. If the more rapid schedule is worth the tradeoff in information format, we will adopt it for Sound-wide mapping.

Potential for SCALE to Fill Gaps in Current Systems

Both of the currently used classification systems fulfill summary information needs. However, both have limited ability to provide detailed information about the quality of different habitats and their resident macro-invertebrate and vegetation communities. A Marine and Estuarine Classification System for Washington State provides the most information with its diagnostic and common species lists, but they are general and not quantitative. This severely limits the degree to which these systems can be used to assess habitat function through community analysis or site comparison. The classification categories are too broad.

The SCALE system was designed to address the limitations of existing systems through its high spatial resolution and its quantification of factors that are known to impact the distribution of biota (Schoch and Dethier, 1996). In summer 1997, we tested the feasibility of using the linked geophysical mapping and biota-sampling model for inventory and monitoring. The SCALE system was initially developed in rocky environments. Our study applied SCALE in soft sediment environments in Carr Inlet, southern Puget Sound. We examined the potential usefulness of the SCALE system in meeting the

PSAMP Nearshore Habitat Program goals of inventorying and monitoring habitat. Methods and results of the research are described in Schoch & Dethier (1997), Schoch & Dethier (1998), and Dethier & Schoch (1998). This section integrates results and conclusions of their research with our own analysis of implications with respect to Nearshore Habitat Program objectives.

The strength of SCALE is that mapping methods are linked to a model for habitat clustering, biota sampling, and community extrapolation. The geophysical data is used to statistically cluster shoreline segments into groups of similar habitat types. Segments are then randomly selected from each group and sampled with quadrats and cores to collect quantitative data on vegetation and macro-invertebrate biota. Sampling results about the abundance and frequency of biota at representative beaches can then be extrapolated to other similar segments with known variation statistics, providing users with quantitative information on the frequency and abundance of vegetation and macro-invertebrates.

The geophysical mapping is designed to nest within less detailed classification systems in order to generalize results over large areas. The highest resolution units are alongshore segments of shoreline of 10 meters or longer, divided into intertidal polygons. Alongshore segments are then grouped into blocks based on wave energy, salinity and sea surface temperature. The next successive levels of partitioning are the embayment, district, and region. In addition to generalization over larger geographic areas, shoreline characteristics can be generalized by nesting within the lower resolution Shoreline Type category in the BC Shore-Zone Mapping System.

SCALE is not ideal for summary information uses. It provides more detailed geophysical and biota data than needed and not enough interpreted information. Additionally, SCALE's high resolution mapping is too resource-intensive to meet the requirement of relatively rapid Sound-wide mapping. While SCALE is not ideal for summary information uses, lower resolution systems fulfill user needs for summary information. SCALE would increase the precision of more advanced data analysis because it:

- Allows for analysis of habitat characteristics by intertidal zone;
- Increases the precision of area calculations;
- Provides biotic community information; and
- Provides detailed geophysical characterization for modeling habitat usage by other species.

SCALE potentially fulfills monitoring goals because it characterizes intertidal habitat health, and links to other valued species. Geophysical characteristics and biotic communities that support physical habitat and food web interactions are described. It samples the community of macro-invertebrates and vegetation based on the assumption that the community as a whole is the broadest metric to monitor for changes in health due to multiple stressors. This allows for multivariate analysis of the community, or univariate analysis of species that are valued or are diagnostic of a condition.

Results of the pilot project in Carr Inlet suggest that community information can be generalized by BC Shore-Zone Mapping System Shoreline Type, and by successively increasing spatial scales. This small area result must be further tested to determine if variation in biota is lowered sufficiently for effective trends monitoring, and if results can be generalized meaningfully over large areas by linking to lower resolution mapping systems. If these results are successful, we see a range of potential uses, including:

- Selecting matched sites for field research or applied monitoring to compare regional differences, effects of degradation, etc.;
- Assessing biotic damage following natural or human-caused events;
- Denoting habitats sensitive to oil spills and other disturbances;
- Predicting resource-rich habitats, or those where key resource species could exist; and
- Generalizing results at multiple sites to characterize regional conditions.

SCALE may not meet PSAMP's monitoring goal to provide an easy to understand measure of habitat health. The majority of species surveyed are not valued directly by the public. Because little is known about the life history and population dynamics of many species, preliminary results may provide more information on knowledge gaps than on health trends. An alternative monitoring approach would be to focus on eelgrass, kelp or other vegetation communities that have recognized ecological importance.

We are continuing to evaluate the SCALE system. The current project tests the concept of nesting SCALE with the BC Shore-Zone Mapping Syste*m* by comparing maps created using each system in the same area, and by aggregating the biota data according to the BC Shore-Zone category of Shoreline Type. The next project will collect biota information from three inlets in South Sound in order to see how variation increases over larger areas.

Implications for Trends Monitoring

The SCALE research has helped to focus a series of questions we must answer prior to initiating a monitoring program to assess nearshore habitat health. Future monitoring needs to be driven by priorities that specify species or habitats of interest, the scale of resolution needed, and the scale of variation that can be accepted. Joint consideration of scientific methods and management issues is required to determine what sampling design tradeoffs best answer the highest priority questions with available resources.

Like other large area monitoring efforts, we lack the resources to survey all habitat types at all tidal levels. Underwood and Petraitis (1993) recommend two alternate approaches for addressing this problem: 1) randomize physical habitat features such that sites selected for experiments or monitoring are "properly representative" of all the habitats in a region; or 2) stratify habitats and then replicate studies only within the chosen strata. The advantage of the first approach is that it gives a statistically valid portrait of an area, the disadvantage is in the high variances that will exist among randomly chosen sites due to physical differences. A well-known method for randomizing habitat features in regional monitoring is the Environmental Mapping and Assessment Program (EMAP). For results of data collection using this random stratified design see Bailey et al. (1998). While the second approach lowers variances and increases the ability to detect change, it requires difficult choices about which habitats to study and which to ignore. Certain regions, habitat types, or species of particular concern would need to be identified.

Carr Inlet study results illustrate potential considerations for selecting priority habitat types for sampling. One criterion is habitat abundance. In Carr Inlet, sand and sand-pebble habitats were most abundant. Species richness is another potential criteria. In Carr Inlet, sand habitats had the most species overall, yet had high variability. Gravel and mud habitats had the highest species richness per sample. Selecting the most sensitive habitats would require identification of the stressors of greatest concern. An alternate approach is to census all habitat types, which sacrifices detail, but gains overall coverage. This was the method in Carr Inlet, where mixed coarse, sand, and mud habitats were sampled.

Another variable to consider in sampling design is tidal elevation. We chose intertidal sampling because these communities contain plants and animals that are diverse, productive, and consumed by a variety of species, including humans. At the interface between land and water, these communitites are directly affected by multiple terrestrial and marine stressors. In addition, they are relatively easy to quantify compared to subtidal communities that require more expensive sampling methods such as scuba diving or remote sensing. Within the intertidal zone, the lower intertidal (sampled at mean lower low water) had the most biomass, yielding the most information per sample. While middle and upper intertidal samples had relatively fewer species, these areas are most directly impacted by recognized threats, including oil spill persistence and shoreline modification. Subtidal sampling is desirable, but the increased sampling costs would require further narrowing of habitat types or regions to be monitored.

The number and size of quadrats, cores and sieves is another tradeoff. Concurrent use of quadrats and cores and 2.0-mmsieves generally worked well for capturing the community of surface-dwelling and infaunal species. Greater sample sizes would better quantify very patchy species. Decreasing the sieve

mesh size would retain more species, and would be compatible with the 1-mm subtidal sampling methods of the Puget Sound Estuarine Protocol. However, estimates predict than the higher resolution would lead to a 50–100% increase in field sorting and laboratory time. Core diameter and depth was not designed to sample clam densities. Common sense and qualitative comparison to other surveys suggests that larger and deeper-dwelling species, such as clams, are under-sampled using this method. However, larger, deeper cores would require an increase in sorting and identification time required.

Funding is an important factor that will limit the range and number of habitats that are monitored. While the Nearshore Program has resources to fund this work, cooperative research with other groups who need habitat inventory and trends monitoring information would increase its scope.

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Probability-Based Estimation of Nearshore Habitat Characteristics

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Introduction

The loss of nearshore habitat is the most significant threat to the health of marine waters in Puget Sound and Georgia Basin (British Columbia/Washington Marine Science Panel, 1994). Because of the ecological importance of these habitats and the threat of continued habitat loss and degradation, there is a high demand by scientists, managers, and policy makers for information about status and trends in marine and estuarine habitats. Unfortunately, the most recent comprehensive inventory of nearshore habitats in Puget Sound, the Coastal Zone Atlas (Washington State Department of Ecology, 1978), is more than 20 years old.

As part of the Puget Sound Ambient Monitoring Program, the Department of Natural Resources (DNR) Nearshore Habitat Program is developing an updated inventory of intertidal habitats through remote sensing, field verification, and a geographic information system (GIS). The inventory has been completed for Whatcom County (Berry and Ritter, 1997), and areas in Skagit and Island Counties are currently being processed. However, at the current rate and level of resources, a complete inventory of Puget Sound will take at least fifteen years to complete.

In order to fill the information gaps more rapidly, DNR is investigating alternative or supplemental approaches for assessing and monitoring nearshore habitats (Berry et al., this volume). The purpose of this study was to test the utility of a probability-based sampling design for characterizing nearshore habitat status and trends in Puget Sound. The sampling design is based on the designs developed for the Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP). The objectives of EMAP are consistent with those of the Puget Sound Ambient Monitoring Program, and include the following (Overton et al., 1990):

- Estimate current status, extent, changes, and trends in indicators of the condition of the nation's ecological resources on a regional basis with known confidence.
- Monitor indicators of pollutant exposure and habitat condition and seek associations between human-induced stresses and ecological condition.
- Provide periodic statistical summaries and interpretive reports on ecological status and trends to resource managers and the public.

This study provides Sound-wide estimates of nearshore habitat distribution and abundance. To facilitate comparison with our inventory, habitats are characterized according to Dethier's (1990) Marine and Estuarine Habitat Classification System and with the same vegetated land-cover classes used for DNR's current mapping program (Berry and Ritter, 1997). In addition, this study estimates the extent of shoreline modification (bulkheads, dikes, fill, etc.) because it is an anthropogenic influence that negatively affects nearshore habitats (Shipman, 1997; Thom et al., 1994). Specifically, the following questions were answered:

1. What proportion of shoreline length has a specific vegetation type, substrate type or shoreline modification?
2. What proportion of intertidal area has a specific vegetation type, substrate type or shoreline modification?

Methods

Sample Design

Sample sites for characterizing nearshore habitat were chosen according to the random tessellation stratified design used for EMAP projects. The details of this sample design are beyond the scope of this paper, but detailed descriptions of the design approach and rationale can be found in Stevens (1997), Stevens (1994), Overton and Stehman (1996), and Overton et al. (1990). The design is probability-based and allows estimation of characteristics of continuous spatial populations with known confidence limits. The general approach is to randomly place a hexagonal grid over the area to be sampled and select one point at random from each grid cell. A variation of this approach is used for linear features, such as shorelines and rivers.

For our survey, we randomly selected 325 sites along 3715 km (2303 mi) of shoreline in Puget Sound (Figure 1). Sites were selected with equal probability, and each site represents 11.4 km (7.1 mi) of shoreline. The equiprobable design allows for greater flexibility and simplicity in future analysis, including post-sampling stratification or characterization of sub-populations. For this paper, we stratified the points according to five oceanographically-based basins (Figure 1); however, other spatial strata could be defined for future analyses of the same data set, as long as there are a minimum of 30–40 sample points in each strata.

Data Collection

Each site was visited in the field to identify the vegetated land cover classes and Dethier (1990) habitat types that were present at that site. The specific classes of interest were:

- vegetation: eelgrass, kelp, green algae, brown algae, red algae, mixed algae, salt marsh, and spit/berm
- substrate: bedrock, boulder, hardpan, cobble, mixed coarse, gravel, sand, mixed fine, mud, organic, artificial

In order to compare this data set with our mapping project, vegetation and substrate classes were assigned according to the predominant characteristics, and a feature had to be at least 1–5 m to be identified as a separate land-cover class or habitat type. (In other words, very narrow bands of vegetation or substrate were generalized into adjacent features).

For the first question, (what proportion of shoreline length has _____?), we identified which vegetation and habitat types were present along a visual transect line, starting at the randomly selected sample site and running perpendicular to the shoreline across the intertidal zone. The focus of the survey was on the intertidal zone, but because of the ecological and policy importance of kelp and eelgrass, subtidal beds of kelp and eelgrass were also documented. The presence of shoreline modification in the intertidal zone and adjacent area was determined after the field survey from a review of the slides of each sample site.

For the second question, (what proportion of intertidal area has _____?), we annotated the transect line and the boundaries of each feature onto an aerial photograph. The across-shore width of the transect and each feature on the transect were measured from the photographs. Across-shore widths of subtidal vegetation (kelp or eelgrass) were not measured and were not included in the areal estimates.

Data Analysis

Data from this study are analyzed for Puget Sound as a whole, and for five oceanographically based sub-basins, South Puget Sound, Central Puget Sound, Northern Puget Sound (Whidbey Subbasin), Hood Canal, and San Juans and Straits (Figure 1). The number of sample sites and shoreline lengths in each basin are given in Table 1.

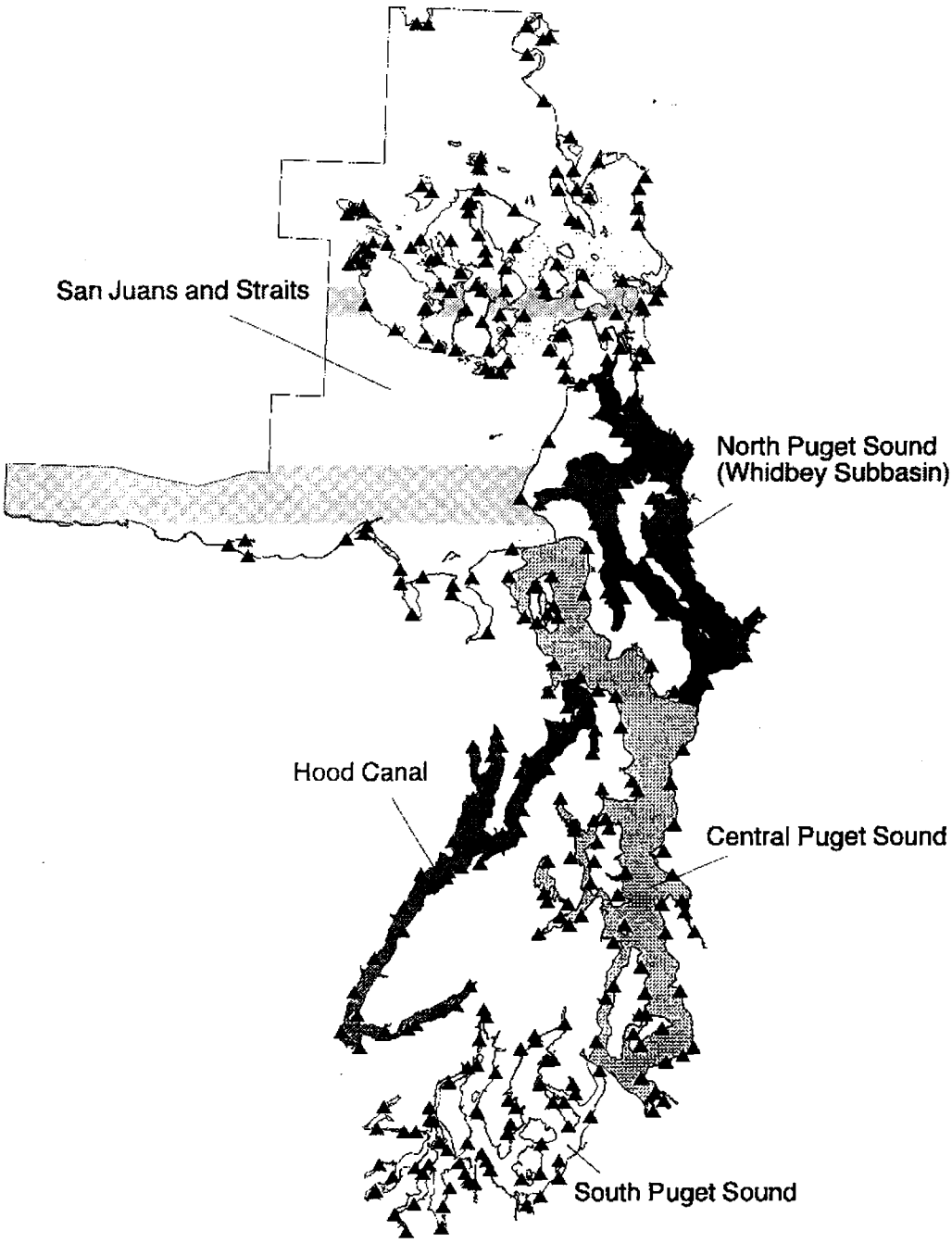

Figure 1. Puget Sound basins and randomly selected habitat survey sites.

Table 1. Number of sample sites and shoreline length by basin.

Basin	# of Sites	Shoreline Length
South Puget Sound (SPS)	64	731.5 km (453.5 mi)
Central Puget Sound (CPS)	71	811.5 km (503.1 mi)
North Puget Sound (NPS)	42	480.0 km (297.6 mi)
Hood Canal (HDC)	34	388.6 km (240.9 mi)
San Juans and Straits (SJS)	114	1302.9 km (807.8 mi)
Total	325	3714.5 km (2303 mi)

To estimate the proportion of shoreline length occupied by a specific feature (vegetation, substrate, human modification), the number of sites with each characteristic are divided by the total number of sample sites in the basin. Because this is a binomial sample (the feature is either present or absent), and each sample has the same weight (equiprobable), the 95% confidence limits are calculated with standard techniques, using the normal approximation for the distribution (Snedecor and Cochran, 1980).

To estimate the proportion of intertidal area occupied by a specific vegetation or substrate type, we used the Horvitz-Thompson ratio estimator. In an equiprobable design, it is the same as dividing the sum of the across-shore widths of a land cover class by the total across-shore widths (transect lengths) in the basin. The variance is calculated using a simplified form of the Horvitz-Thompson variance estimator (see Stevens, 1997, for general estimating equations), and 95% confidence limits are calculated as above.

Finally, the estimates for proportion of shoreline with kelp, eelgrass, and human modification were compared to existing data sets to assess the accuracy of these estimates, as well as to assess trends.

Results

Vegetation

For Puget Sound as a whole, the most common vegetated habitat, as a proportion of shoreline length, is composed of green algae, which cover 28.3% of the shoreline (Table 2). Eelgrass is the second most common vegetated habitat occurring on 23.4% of the total shoreline. The least frequently occurring vegetation type is kelp, which covers only 7.1% of the shoreline length in Puget Sound. The relative frequency of each vegetation type is quite different for each basin. In South Puget Sound (SPS), which has the least amount of total vegetated habitat, salt marsh is the most common vegetated habitat (21.9%). In Hood Canal (HDC), eelgrass is the most common vegetation type (32.4%), and kelp (0.0%) and green algae (5.9%) are the least common. Central Puget Sound (CPS) has the most 'typical' pattern of vegetation abundance, with green algae as the most common vegetation type (40.8%), eelgrass as the second most abundant (22.5%), and kelp as the least common vegetation type (2.8%). In Northern Puget Sound (NPS), green algae and eelgrass are equally abundant, each covering 40.5% of the shoreline. Finally, green algae are the most common vegetation in the San Juans and Straits (SJS), covering 29.8% of the shoreline. However, eelgrass and mixed algae are almost as abundant, both covering 27.2% of the shoreline. Spit or berm vegetation is the least common vegetated habitat (10.5%) in the San Juans and Straits. When all vegetation types are considered together, 72.3% of Puget Sound's shoreline has some vegetated habitat. By basin, the San Juans and Straits have the most vegetation—87.7% of the shoreline length has some vegetated habitat. South Puget Sound is the least vegetated (42.2%). Finally, the confidence limits for these estimates are generally between 3–10%.

Table 2. Estimates of percent of shoreline length with each vegetation type and 95% confidence limits.

	All PS		South Puget Sound		Central Puget Sound		North Puget Sound		Hood Canal		San Juans/ Straits	
Vegetation type	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)
brown algae	7.7%	4.6%	0.0%	0.0%	5.6%	5.4%	7.1%	7.8%	8.8%	9.5%	13.2%	6.2%
green algae	28.3%	3.9%	15.6%	8.9%	40.8%	11.4%	40.5%	14.8%	5.9%	7.9%	29.8%	8.4%
kelp	7.1%	4.9%	0.0%	0.0%	2.8%	3.8%	2.4%	4.6%	0.0%	0.0%	17.5%	7.0%
mixed algae	14.8%	3.9%	6.3%	5.9%	9.9%	6.9%	2.4%	4.6%	14.7%	11.9%	27.2%	8.2%
eelgrass	23.4%	2.8%	1.6%	3.0%	22.5%	9.7%	40.5%	14.8%	32.4%	15.7%	27.2%	8.2%
salt marsh	15.1%	2.9%	21.9%	10.1%	7.0%	6.0%	19.0%	11.9%	23.5%	14.3%	12.3%	6.0%
spit/berm	7.7%	2.9%	3.1%	4.3%	5.6%	5.4%	11.9%	9.8%	5.9%	7.9%	10.5%	5.6%
all vegetation	72.3%	4.9%	42.2%	12.1%	69.0%	10.8%	81.0%	11.9%	73.5%	14.8%	87.7%	6.0%

The patterns of vegetation abundance are somewhat different when estimated as a percentage of intertidal area (Table 3). From the areal estimates, eelgrass is the most abundant vegetation type for Puget Sound as a whole, covering 19.3% of the intertidal area. Salt marsh is the second most common vegetated habitat (6.8%) and green algae follows (5.3%). The four remaining vegetation types (brown algae, kelp, mixed algae, and spit/berm) cover only 2.7% of the intertidal area of Puget Sound. Areal estimates for each basin indicate that one or two vegetation types are often highly abundant relative to the other types. For example, in the San Juans and Straits, eelgrass covers 42.2% of the intertidal area, whereas none of the other vegetation types cover more than 4.4% of the intertidal area. For Puget Sound as a whole, 33.9% of the intertidal area is covered with vegetation. Similar to the linear estimates, South Puget Sound is the least vegetated basin—only 12.7% of the intertidal area has vegetation. San Juans and Straits have the most intertidal vegetation coverage (53.3%). Confidence limits are generally on the same order as the estimates, ranging from 0.1% to 37.8%.

Table 3. Estimates of percent of intertidal area with each vegetation type and 95% confidence limits.

	All PS		South Puget Sound		Central Puget Sound		North Puget Sound		Hood Canal		San Juans/ Straits	
Vegetation type	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)
brown algae	0.5%	0.3%	0.0%	0.0%	0.5%	0.7%	0.3%	0.4%	0.6%	0.9%	0.7%	0.7%
green algae	5.3%	2.2%	2.1%	1.9%	12.0%	4.4%	6.8%	6.2%	2.2%	4.4%	4.4%	3.7%
kelp	0.2%	0.1%	0.0%	0.0%	0.2%	0.3%	0.0%	0.0%	0.0%	0.0%	0.4%	0.4%
mixed algae	1.3%	0.6%	0.6%	0.9%	1.8%	1.5%	0.0%	0.0%	1.4%	1.9%	2.1%	1.5%
eelgrass	19.3%	12.3%	0.2%	0.4%	11.4%	6.6%	6.5%	5.8%	5.4%	6.3%	42.2%	27.2%
salt marsh	6.8%	4.0%	9.7%	14.7%	2.0%	3.1%	9.0%	9.4%	18.0%	8.8%	2.5%	2.4%
spit/berm	0.7%	0.4%	0.0%	0.1%	0.5%	0.6%	1.1%	1.4%	0.2%	0.3%	0.9%	0.6%
vegetation	33.9%	14.9%	12.7%	15.5%	28.3%	10.4%	23.6%	8.8%	27.8%	22.3%	53.3%	37.8%

Substrate

The estimates and confidence intervals for the percent of shoreline length and intertidal area with each substrate type are given in Tables 4 and 5. As a percentage of the entire shoreline of Puget Sound, the most abundant substrate types are mixed fine (39.4%), mixed coarse (35.4%), gravel (32.3%), and

sand (25.2%). Most Puget Sound basins have a similar pattern of substrate abundances, although Hood Canal has quite a bit more gravel (52.9%) and the San Juans and Straits have a high frequency of bedrock (27.2%) and boulder (18.4%) habitats. Similar to the vegetated habitats, usually two or three substrates comprise the majority of the intertidal area. For all Puget Sound, mixed fine (38.0%), sand (32.2%), and mud (14.8%) are the most common substrates. For the basins, two or three of these same substrates are also the most common substrate types, except for Central Puget Sound where the third most common substrate type is mixed coarse (17.1% of the intertidal area).

Table 4. Estimates of percent of shoreline length with each substrate type and 95% confidence limits.

	All PS		South Puget Sound		Central Puget Sound		North Puget Sound		Hood Canal		San Juans/ Straits	
Substrate type	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)
artificial	8.0%	3.0%	1.6%	3.0%	14.1%	8.1%	7.1%	6.3%	5.9%	7.9%	8.8%	5.2%
bedrock	12.3%	3.6%	1.6%	3.0%	2.8%	3.8%	9.5%	7.2%	5.9%	7.9%	27.2%	8.2%
boulder	7.1%	2.8%	0.0%	0.0%	0.0%	0.0%	2.4%	3.7%	2.9%	5.7%	18.4%	7.1%
hardpan	0.6%	0.9%	1.6%	3.0%	1.4%	2.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
cobble	5.2%	2.4%	0.0%	0.0%	4.2%	4.7%	4.8%	5.2%	17.6%	12.8%	5.3%	4.1%
mixed coarse	35.4%	5.2%	34.4%	11.6%	49.3%	11.6%	35.7%	11.7%	35.3%	16.1%	27.2%	8.2%
gravel	32.3%	5.1%	43.8%	12.2%	31.0%	10.8%	33.3%	11.5%	52.9%	16.8%	20.2%	7.4%
mixed fine	39.4%	5.3%	56.3%	12.2%	31.0%	10.8%	31.0%	11.3%	35.3%	16.1%	39.5%	9.0%
sand	25.2%	4.7%	17.2%	9.2%	35.2%	11.1%	40.5%	12.0%	26.5%	14.8%	17.5%	7.0%
mud	10.8%	3.4%	25.0%	10.6%	8.5%	6.5%	9.5%	7.2%	5.9%	7.9%	6.1%	4.4%
organic	1.5%	1.3%	1.6%	3.0%	0.0%	0.0%	2.4%	3.7%	2.9%	5.7%	1.8%	2.4%

Table 5. Estimates of percent of intertidal area with each substrate type and 95% confidence limits.

	All PS		South Puget Sound		Central Puget Sound		North Puget Sound		Hood Canal		San Juans/ Straits	
Substrate type	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)
artificial	0.4%	0.2%	0.1%	0.1%	1.1%	0.7%	0.2%	0.4%	0.2%	0.6%	0.4%	0.4%
bedrock	1.3%	0.6%	0.1%	0.1%	0.7%	1.0%	0.4%	0.4%	0.4%	0.9%	2.7%	1.5%
boulder	0.7%	0.4%	0.0%	0.0%	0.0%	0.2%	0.2%	0.4%	0.1%	0.6%	1.8%	1.0%
hardpan	0.0%	0.1%	0.1%	0.1%	0.2%	0.4%	0.0%	0.2%	0.0%	0.5%	0.0%	0.4%
cobble	0.5%	0.3%	0.0%	0.0%	0.4%	0.6%	0.4%	0.6%	1.8%	1.6%	0.4%	0.6%
mixed coarse	6.2%	1.2%	5.7%	2.6%	17.1%	5.7%	3.7%	1.9%	4.4%	2.6%	4.3%	1.7%
gravel	5.5%	1.4%	11.1%	4.9%	7.5%	4.3%	4.7%	3.7%	4.4%	2.5%	3.2%	1.6%
mixed fine	38.0%	19.6%	22.9%	16.1%	28.7%	21.2%	25.6%	18.9%	18.0%	18.5%	61.2%	49.7%
sand	32.2%	18.2%	21.7%	23.9%	38.6%	26.7%	61.4%	65.5%	16.7%	13.7%	22.6%	27.5%
mud	14.8%	11.3%	38.3%	29.3%	5.8%	4.7%	3.0%	4.6%	53.4%	89.3%	2.6%	2.9%
organic	0.4%	0.4%	0.2%	0.3%	0.0%	0.2%	0.3%	0.7%	0.5%	1.2%	0.6%	0.8%

Shoreline Modification

The estimates of percentage of shoreline length with human modification (bulkheads, boat ramps, fill, etc.) Is shown in Table 6. Central Puget Sound has the most modified shoreline (52.1%), and the San Juans and Straits have the least modification (20.2%). 33.2% of all Puget Sound shorelines have been modified or armored.

Table 6. Estimates of percent of shoreline length with human modification and 95% confidence limits.

	All PS		South Puget Sound		Central Puget Sound		North Puget Sound		Hood Canal		San Juans/ Straits	
	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (±)	%	conf (_)
shoreline modification	33.2%	5.1%	34.4%	11.6%	52.1%	11.6%	35.7%	11.7%	32.4%	15.7%	20.2%	7.4%

Comparison with Other Data

The linear estimates of eelgrass, kelp, and shoreline modification were compared to existing inventories to assess the accuracy of the estimates and to look for trends. The eelgrass estimates were compared to eelgrass data from the Coastal Zone Atlas (Washington State Department of Ecology, 1978). The values from the Coastal Zone Atlas (CZA) are within the confidence limits of the DNR estimates, except for Central Puget Sound, where there is more eelgrass in CZA than estimated from DNR's survey, and North Puget Sound, where there is less eelgrass in CZA than found by DNR (Table 7).

Table 7. Comparison of DNR's estimates of percentage of shoreline length with eelgrass to values from Coastal Zone Atlas (CZA) (Washington State Dept. of Ecology, 1978).

Basin	CZA (1978)	DNR (1995)
South Puget Sound	4.3%	1.6% ±3.0%
Central Puget Sound	34.4%	22.5% ±9.7%
North Puget Sound	20.1%	40.5% ±14.8%
Hood Canal	39.1%	32.4% ±15.7%
San Juans & Straits	21.0%	27.2% ±8.2%
All	22.4%	23.4% ± 2.8%

The linear extent of kelp determined from other data sources (Thom and Hallum, 1991; Washington State Department of Ecology, 1978), is generally within the confidence limits of DNR's probability-based estimates. Based on this series of data there is no clear trend in kelp abundance over time in Puget Sound.

Table 8. Comparison of DNR's estimates of percentage of shoreline length with kelp to values from Rigg, 1912 and Washington Department of Wildlife, 1977 (both in Thom and Hallum, 1991), and Coastal Zone Atlas (CZA) (Washington State Dept. Of Ecology, 1978).

Basin	Rigg (1912)	WDW (1977)	CZA (1978)	DNR (1995)
South Puget Sound	1.5%	6.4%	3.5%	0.0% ±0.0%
Central Puget Sound	2.4%	14.1%	3.9%	2.8% ±3.8%
North Puget Sound	4.8%	11.0%	0.0%	2.4% ±4.6%
Hood Canal	0.5%	0.3%	0.0%	0.0% ±0.0%
San Juans & Straits	16.3%	17.3%	10.1%	17.5% ±7.0%
All	7.8%	12.0%	5.1%	7.1% ±4.9%

The estimated linear extent of shoreline modification was compared to data from surveys by Morrison et al. (1993) and Shipman, 1992–1994 (published 1997). The existing surveys are generally within the confidence intervals of the DNR probability-based estimates.

Table 9. Comparison of DNR's estimates of percentage shoreline length with human modification to values from Morrison et al. (1993) and Shipman 1992–1994 (published 1997).

Basin	Morrison (1993)	Shipman (1992–1994)	DNR (1995)
South Puget Sound	29% (Thurston Co.)	25% (Fox Is.)	34.4% ±11.6%
		29% (Stretch Is.)	
Central Puget Sound		49% (Tracyton)	52.1% ±11.6%
		59% (Point Monroe)	
		24% (Brownsville)	
North Puget Sound		20% (Holmes Harbor)	35.7% ±11.7%
Hood Canal			32.4% ±15.7%
San Juans & Straits		13% (Birch Point)	20.2% ±7.4%
All			33.2% ±5.1%

Discussion

Characterization of Nearshore Habitats

The probability-based sampling approach used in this study provides estimates of habitat abundance for Puget Sound and general habitat distribution between five subbasins. Because of the demonstrated differences in habitat type and abundance between basins, spatial stratification by subbasin provides critical regional context for many purposes, such as trend analysis, assessment of habitat quality, and setting restoration goals. In addition, estimates of habitat by shoreline length and by intertidal area provide different results; therefore, the measure to be used for a particular purpose should be chosen carefully. Finally, no obvious trends in kelp or eelgrass abundance were seen when comparing this data set to previous inventories. However, these results must be interpreted with caution because different methods were used in each of these inventories.

Assessment of Probability-Based Sampling Design

The probability-based sampling design has several strengths. First, the accuracy of the probability-based estimates of habitat distribution and abundance is fairly high, as demonstrated by the agreement of these estimates with previously published data sets. Second, the ability to calculate confidence intervals provides a precision for assessing habitat change. Third, although the design is quite complex, the analysis is fairly simple. Finally, the equiprobable design allows for a great deal of flexibility in future analysis; different stratifications or subpopulations (such as, eelgrass vs. no eelgrass) can be defined and analyzed after the data has already been collected.

There are also two main disadvantages of this sampling approach. First, it does not provide site-specific information for specific projects or site assessment. Second, although confidence intervals can be calculated, the precision of these estimates, particularly the areal estimates, may be too low to detect change at the level that is necessary for long-term monitoring.

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The Citizen Shoreline Inventory

Chrys Bertolotto
Adopt a Beach

Abstract

The Citizen Shoreline Inventory is a new program (started 2/97) that unites two goals: 1) to fill the information gaps that exist about Puget Sound's shoreline habitat condition and extent, and 2) to provide an opportunity to educate and train community members about the value of shorelines (generally beaches, estuaries and adjacent land uses) and the impacts that we, as a society, have upon them. The findings of the inventory will be displayed and updated in a Citizen Shoreline Atlas, a series of living map-based documents available on a Geographic Information System linked to the Internet. Data will also be available in a database (Excel) format.

This paper will address several points:

- Practical uses, to date, of the data by watershed planners, researchers, land use managers, and community assessment of sensitive sites;
- Basic statistical findings on completeness of the pilot efforts (ending 12/97);
- Data management, quality assurance, quality control, and shoreline criteria plans (these will be outlined to address commonly stated concerns about volunteer monitoring; basic premises, partnership and advisory roles in creating and refining the program);
- Format of the Atlas will be shown via overheads (or slides); and
- Expected future of program.

Analysis of pilot studies was to be completed in January 1998, but indications show that the inventory will be able to create a pool of information that is useful and creates a constituency among the general public that believes our shores are worthy of extra protection efforts.

DFO's Pacific Region Shorekeeper's Initiative

Glen S. Jamieson, Colin Levings, and Brian Smiley
Department of Fisheries and Oceans Canada

Abstract

There are presently no long-term databases describing community structure for intertidal ecosystems in British Columbia. Short-term documentation exists, along with some longer-term data on specific species, notably commercial clams, but these do not consider the broad ecosystem. In recent years, stimulated in part by urbanization in the Strait of Georgia and concern about possible effects of global warming, there has been increased interest in developing protocols to facilitate long-term data collection. Some proposals have been initiated by NGOs, but these have tended to focus more on education of the public rather than rigorous data collection and database maintenance. As a response, we have developed a protocol termed the "Shorekeeper's Guide" which will be made available to the public. This protocol has been developed as a series of modules that allow individuals or community groups to survey the intertidal to a degree that meets their ability and interests. However, intrinsic to all modules are procedures for standardization of data collection, recording, and maintenance. Data collection is based around identification of biological structure in habitats determined by physical characteristics. This talk will describe progress to date and the results of an extensive field evaluation of the protocol.

PUGET SOUND RESEARCH '98

SESSION 5B

SEDIMENT EVALUATION AND CLEANUP

Session Chair:
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Assessing Long-Term Physical Stability and Benthic Infaunal Colonization of a Sediment Cap Placed over Chemically Contaminated Bottom Sediments in the Wyckoff/Eagle Harbor Superfund Site, Bainbridge Island, Washington

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Introduction

A sediment cap was placed over chemically contaminated sediments in Eagle Harbor, Washington as part of a cleanup action at the Wyckoff/Eagle Harbor Superfund Site (U.S. EPA et al., 1994). The Wyckoff/Eagle Harbor Superfund Site is located on the eastern side of Bainbridge Island, Washington, approximately six nautical miles west of Seattle (Figure 1). The site was added to the U.S. EPA National Priorities List of Superfund Sites in 1987. Several studies, including a remedial investigation and feasibility study (RI/FS) conducted by the EPA identified elevated levels of polycyclic aromatic hydrocarbons (PAHs) and mercury in marine sediments in the East Harbor (CH_2M Hill, 1989, 1991a, 1991b). Total PAH concentrations in East Harbor sediments ranged from greater than 10,000 parts per billion (µg/kg) to as high as 30,000,000 µg/kg at the "hot spot" (Tetra Tech, 1986). The principal source for the PAHs is a now inactive wood-treatment facility located on the south side of the harbor which treated wood pilings with creosote to prevent biological fouling and shipworm decay. The wood-treatment facility began operations in 1903 and was still in operation as late as 1988. Mercury is believed to have entered the harbor from ship sand-blasting and maintenance by former shipyards located on the northwest shore of Eagle Harbor. Mercury levels in the East and West Harbor sediments exceed the Washington State Sediment Management Standards Minimum Cleanup Levels (Washington Administrative Code [WAC] 173-204-520; Ecology, 1996).

Removal Action

On June 15, 1993, EPA issued an Action Memorandum initiating the first phase of cleanup of the East Harbor Operable Unit (OU) under CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act). The first cleanup phase under the Removal Action consisted of capping the contaminated sediments in the East Harbor where biological effects had been documented (CH2M Hill, 1989). The sediment cap was constructed to physically isolate the contaminated sediments from the marine environment, to prevent heavily contaminated areas from acting as a source of contamination to other areas of Eagle Harbor, to provide clean habitat for sediment-dwelling organisms, and to bring surface sediments in the East Harbor into compliance with the Washington State Sediment Management Standards Minimum Cleanup Levels (Ecology, 1996).

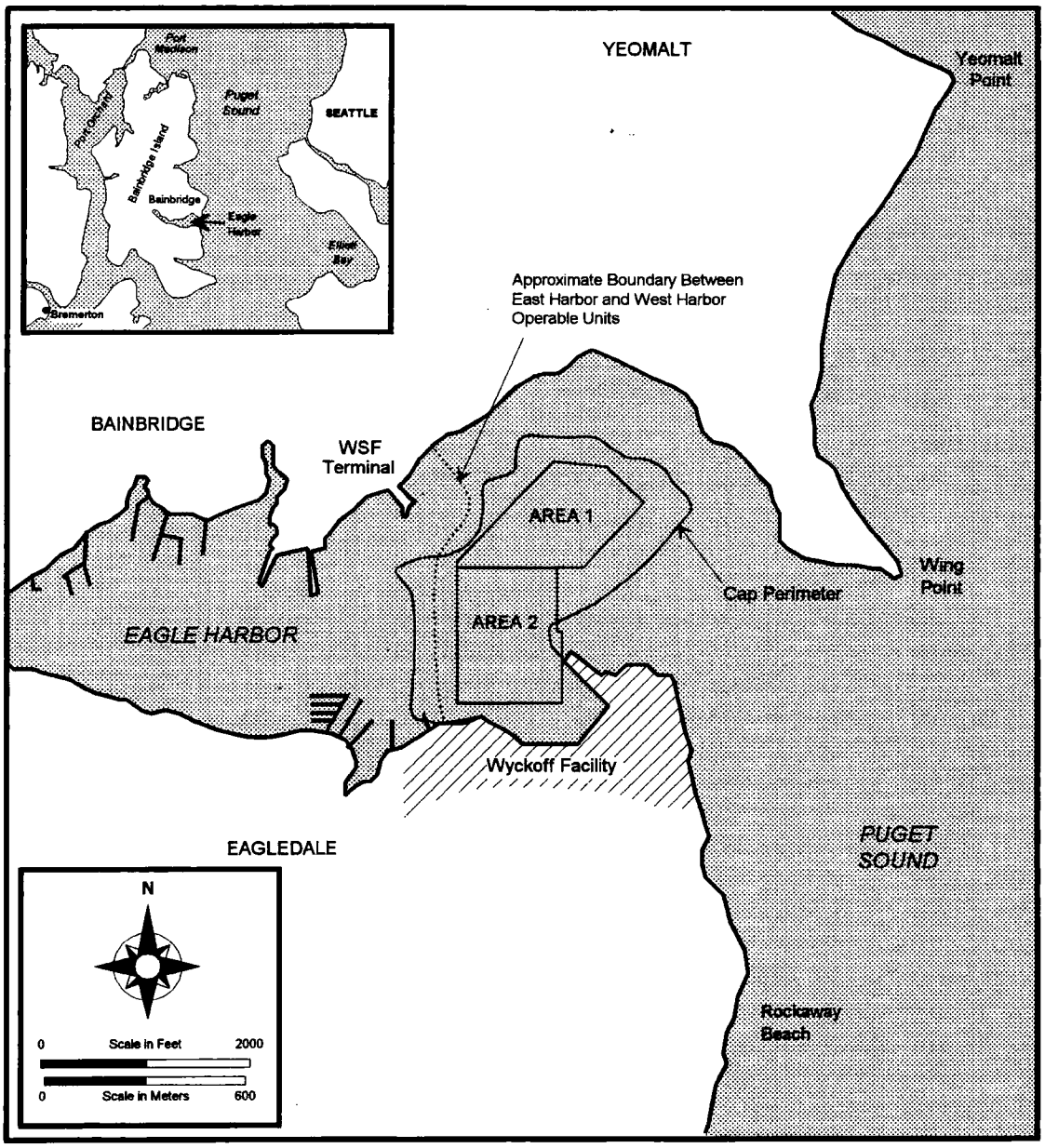

Figure 1. Wyckoff/Eagle Harbor Superfund site, East Harbor operable unit.

The design, construction, and long-term monitoring of the East Harbor sediment cap was conducted by the U.S. Army Corps of Engineers, Seattle District for the EPA, Region 10. The cap was constructed between September 1993 and March 1994. Approximately 136,900 cubic yards (211,000 cubic meters) of clean sandy sediment dredged from the Snohomish River federal navigation channel were placed over 54 acres (21.4 hectares) of chemically contaminated bottom sediment. Cap material placement was conducted by split-hull barge in the more consolidated northern areas of the East Harbor (Area 1), and by hydraulic wash-off from a flat-deck barge in the less consolidated southern areas (Area 2). Final thickness of the sediment cap ranged from one to six feet (0.3 to two meters). A contoured thickness map based on a post-cap placement sub-bottom sonar survey is presented in Figure 2.

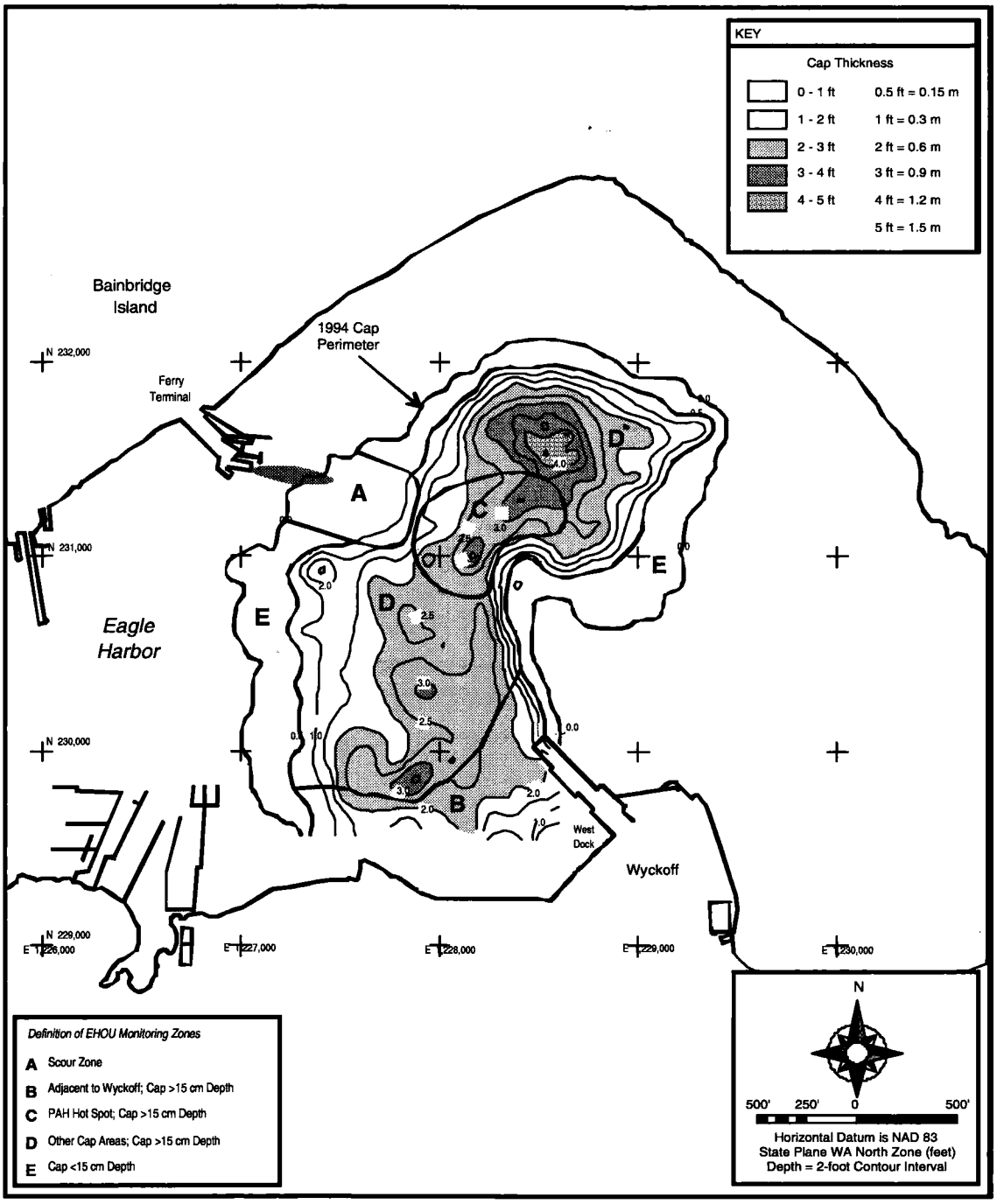

Figure 2. Contour of cap thickness determined by the post-placement sub-bottom sonar survey. Cap monitoring zones are also displayed.

Long-Term Monitoring

Long-term monitoring of the sediment cap is required to ensure that the cap is physically stable and remaining in place at the desired thickness, and to determine whether the cap sediments are providing suitable habitat for bottom-dwelling (benthic) organisms. Monitoring of surface sediment cap chemistry to ensure compliance with the Washington State Sediment Management Standards and monitoring of sub-surface sediment chemistry to assess whether upward migration of contaminants are occurring are also important objectives in the long-term monitoring of the cap, but

are not addressed in this paper. Readers interested in sediment chemistry results for the long-term monitoring program are encouraged to contact the EPA Region 10, in Seattle, Washington.

During the design process of the sediment cap, it was acknowledged that portions of the cap could be affected by erosion, based on modeling presented in the Remedial Investigation (CH_2M Hill, 1989). The main source of erosive energy is the propeller wash from commuter ferries. The Washington State Department of Transportation ferry terminal for the Bainbridge Island-to-Seattle route is located on the north shore of Eagle Harbor. Long-term physical stability results will be used to refine the limits of the erosive areas and cap armoring will be designed, if necessary.

Following completion of the East Harbor OU sediment cap, monitoring zones were defined for the different areas of the cap, based on the existing physical and chemical environments (Figure 2). Monitoring zones were defined for the following cap conditions:

Zone A: This scour area is near the ferry terminal, where cap erosion is most likely due to ferry propeller wash.

Zone B: This depositional area is adjacent to the Wyckoff property and has the potential for surface re-contamination. Cap thickness ranges from 0.5 ft (15 cm) to more than 2.5 ft (>75 cm).

Zone C: Cap area where underlying sediments are highly contaminated ("hot spot"). There is potential for scouring based on its proximity to Zone A. Cap thickness in this zone is generally greater than 2 ft (> 60 cm).

Zone D: Cap areas not adjacent to contaminant sources or erosional forces. Cap thickness ranges from 0.5 ft (15 cm) to greater than 4 ft (> 120 cm) in some areas.

Zone E: Periphery of the sediment cap where cap thickness is 0.5 ft or less (≤ 15 cm).

Methods

The principal tools for assessing cap physical stability are the sequential measurement of cap thickness using precision bathymetric surveys (acoustic seafloor mapping) and REMOTS® (Remote Ecological Monitoring of the Seafloor) sediment profile photography. Determining whether cap sediments are providing suitable habitat for benthic infauna is also assessed using REMOTS® photography.

Precision Bathymetric Surveys

Precision bathymetric surveys (acoustic seafloor mapping) were conducted in the East Harbor using an Odom DF3200 Echotrac® fathometer with a narrow-beam 208-kHz transducer integrated with a portable navigation and survey system for automated data acquisition. Navigation was provided by a differential global positioning system (DGPS) with a positional accuracy of ±2 meters in real time. Depth soundings and position data were recorded at one-second intervals. Depth data were corrected for speed-of-sound in seawater, vessel draft (depth of the transducer below the water surface), and tides. Speed-of-sound corrections were measured using a Sea-Bird SeaCat CTD profiler and tidal corrections to Mean Lower Low Water (MLLW) were obtained from the Seattle, Washington NOAA tide station.

Following completion of each bathymetric survey, the survey data was edited, filtered, and correction factors were applied. Individual survey lanes were edited and outliers (e.g., bubbles from ferry propeller wash) were deleted from the database. To compare bathymetric surveys and assess cap stability, the depth data points for each survey were gridded into an array (matrix) of equally spaced cells. One depth value was calculated for each cell using a weighted average interpolation algorithm. By comparing survey grids between years, areas where changes in cap thickness have occurred can be identified. Survey data processing and gridding were conducted using processing software developed

by SAIC, and Surfer® version 6.0. Depth difference comparisons between bathymetric surveys can show changes in cap thickness that are greater than or equal to 1 foot (≥ 60 cm).

REMOTS® Sediment Profile Photography

REMOTS® is a standardized method developed for sediment profile image collection, analysis, and interpretation (Rhoads and Germano, 1982; 1986). The REMOTS® camera can obtain in-situ profile images of up to 20 centimeters (cm) of the upper sediment column. Profile images collected in Eagle Harbor were used to locate the perimeter of the sediment cap and measure cap thickness in thinly capped areas (Zone E). Sediment profile photography is used by the Dredged Material Management Program (DMMP) to conduct environmental monitoring and mapping of dredged material disposal sites in Puget Sound (SAIC, 1992; 1994; 1996). In addition to cap material mapping, several biological parameters were measured from the REMOTS® images to provide an indication of sediment habitat quality.

Sediment profile photographic images are collected using a Benthos model 3731 sediment-profile camera (Benthos, Inc., North Falmouth, MA) (Figure 3). The sediment-profile camera consists of a wedge-shaped prism with a Plexiglas face plate and a back mirror mounted at a 45° angle. Light is provided by an internal strobe. The mirror reflects the image of the profile of the sediment-water interface up to a 35-mm camera that is mounted horizontally on top of the prism.

The camera prism is mounted on an assembly that can be moved up and down within a stainless steel frame by allowing tension or slack on the winch wire. The rate of fall of the prism (6 cm/second) is controlled by an adjustable passive hydraulic piston, which minimizes the disturbance of the sediment-water interface. A trigger is tripped on impact with the bottom, activating a 13-second time delay on the shutter release; this allows maximum penetration of the prism before a photograph is taken. When the camera is raised from the bottom, a wiper blade automatically cleans off any sediment adhering to the prism faceplate, the film is advanced, and the strobes are recharged. A Benthos Model 2216 pinger is coupled to the camera frame so that the camera can be acoustically tracked to the bottom. The ping rate doubles for a period of 10 seconds after each photograph is taken, verifying image acquisition.

Physical and biological parameters are measured directly from the REMOTS® transparencies using a video digitizer and computer image analysis system. The image analysis system can discriminate up to 256 different tonal color scales, so subtle features can be accurately digitized and measured. The image analysis software allows the measurement and storage of data from up to 21 different variables for each image. The specific REMOTS® parameters used for the long-term monitoring of the East Harbor sediment cap include cap material distribution, sediment grain size major mode, surface boundary roughness, apparent Redox Potential Discontinuity (RPD) depth, infaunal successional stage, and calculation of the organism-sediment index (OSI).

Cap Material Distribution

Measuring the distribution and thickness of the East Harbor sediment cap in sediment profile images depends on optical differences in sedimentary characteristics of the cap material compared to the ambient seafloor. Recently deposited dredged material at a disposal site (or capping site) will typically have unique textural and fabric properties relative to ambient sediments. The dredged material may have a reduced, poorly sorted and chaotic sedimentary fabric if deposited rapidly, or it may show sorted grain-size layers due to discreet depositional events. The dredged material can be clearly distinguished when compared to homogeneous, oxidized, olive-colored surface sediments typical of undisturbed ambient conditions. Because the sediment profile camera is limited to the upper 15 to 20 cm of the sediment column, actual cap thickness measurements using the REMOTS ® camera were made only where ambient sediments were visible (thinly capped areas). REMOTS® photography was effective in mapping the perimeter of the sediment cap.

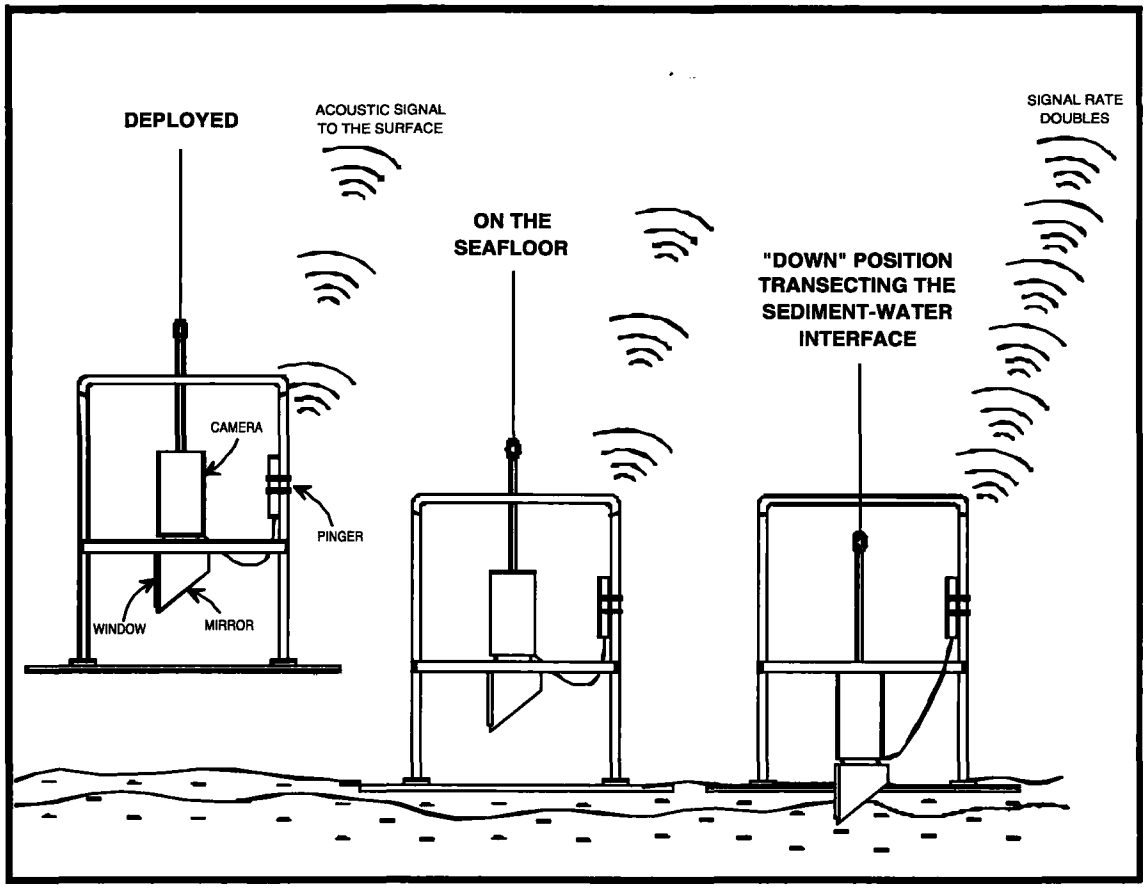

Figure 3. Diagram of the Benthos Model 3731 sediment-profile camera in operational mode.

Sediment Grain-Size

The sediment grain-size major mode and range, in phi units, were visually determined from the sediment profile images by overlaying a grain-size comparator at the same scale. This comparator was prepared by photographing a series of Udden-Wentworth size classes (equal to or less than coarse silt up to granule and larger sizes) through the REMOTS® optical system. Seven grain-size classes are on this comparator: ≥ 4 phi (≤ 0.0156 mm; silt/clay), 4-3 phi (0.0625 - 0.125 mm; very fine sand), 3-2 phi (0.125 - 0.25 mm; fine sand), 2-1 phi (0.25 - 0.50 mm; medium sand), 1-0 phi (0.50 - 1.00 mm; coarse sand), 0-(-1) phi (1.00 - 2.00 mm; very coarse sand), and <-1 phi (> 2.00 mm; gravels). The lower limit of optical resolution is about 62 μm, allowing recognition of grain sizes equal or greater than coarse silt. The accuracy of this method has been documented by comparing REMOTS® estimates with grain-size statistics determined from laboratory sieve analyses (SAIC, 1986).

Surface Boundary Roughness

Surface boundary roughness was determined by measuring the vertical distance (parallel to the film border) between the highest and lowest points of the sediment-water interface. In addition, the origin (physical or biogenic) of this small-scale topographic relief is recorded. In sandy sediments, boundary roughness can be a measure of sand-wave height. On silt-clay bottoms, boundary roughness values often reflect biogenic features such as fecal mounds or surface burrows. These

features are abundant only in areas where boundary shear stresses are low enough that such delicate features are preserved. Disposed dredged material often introduces high surface relief on an otherwise "smooth" bottom. Other surface features are noted when evident, including shell fragments/lag deposits, mud-clay clasts, and wood debris.

Apparent Redox Potential Discontinuity (RPD) Depth

The upper surface of aerobic fine-grained sediments has a higher light reflectance value relative to underlying hypoxic or anoxic sediments. This is readily apparent in REMOTS® images and is due to oxidized surface sediment that contains minerals in an oxidized state (typically an olive brown color), while the reduced sediments below this oxygenated layer are generally gray to black. The boundary between the colored ferric hydroxide surface sediment and underlying sediment is called the apparent redox potential discontinuity (RPD).

The actual RPD is the boundary that separates the positive Eh region (presence of free oxygen) of the sediment column from the underlying negative Eh region (absence of free oxygen). The exact location of the Eh boundary (where Eh=0) can only be determined with microelectrodes. Therefore, the reflectance boundary observed in the REMOTS® images is termed the apparent RPD. In general, the depth of the actual RPD will be shallower than the depth of the apparent RPD, because bioturbating organisms mix ferric hydroxide-coated particles downward below the Eh=0 horizon. As a result, the apparent RPD depth provides an estimate of the degree of biogenic sediment mixing. This variable is important in evaluating the effect of colonizing benthos on disposed sediments. Bioturbation vertically transports buried reduced compounds to the sediment surface and exposes them to an oxidizing water column (Aller, 1982). Bioturbation also affects sediment transport by changing the physical properties of sediments and their mechanical behavior (Rhoads and Boyer, 1982).

Infaunal Successional Stage

The mapping of infaunal successional stages from sediment profile images is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor disturbance. This theory states that primary succession results in "the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. These invertebrates interact with sediments in specific ways. Because functional types are the biological units of interest, our definition does not demand a sequential appearance of particular invertebrate species or genera" (Rhoads and Boyer, 1982). This theory is formally developed in Rhoads and Germano (1982) and Rhoads and Boyer (1982) and is based on a large body of observations from water depths of less than 30 meters.

In shallow water environments, infaunal succession following a major seafloor disturbance initially involves pioneering populations (Primary or Stage I succession) of very small organisms that live at, or near, the sediment-water interface (Pearson and Rosenberg, 1978; Rhoads and Germano, 1986). In the absence of further disturbance, these early successional assemblages are eventually replaced by infaunal deposit feeders; the start of this "infaunalization" process is designated as Stage II. Large, deep-burrowing infauna, or Stage III taxa, represent a high-order successional stage typically found in areas of low disturbance.

Many deep-burrowing infauna feed at depth in a head-down orientation. The localized feeding activity results in distinctive excavations called feeding voids. Diagnostic features of these feeding structures include a generally semicircular shape with a flat bottom and arched roof, and a distinct granular change in the sediment particles overlying the floor of the structure. The relatively coarse-grained material represents particles rejected by the head-down deposit-feeder, as these deep-dwelling infauna preferentially ingest the finer sediment particles. Other subsurface structures, including burrows or methane bubbles, do not exhibit these characteristics. The bioturbation activities of these deposit-feeders are responsible for aerating the sediment and causing the apparent RPD depth to be located several centimeters below the sediment-water interface.

Organism-Sediment Index

The Organism-Sediment Index (OSI) provides a measure of general benthic habitat quality in shallow water environments based on dissolved oxygen conditions, depth of the apparent RPD, infaunal successional stage, and presence or absence of sedimentary methane (Rhoads and Germano, 1986). The OSI is a numerical index ranging from -10 to +11. The lowest value is given to bottom sediments with low or no dissolved oxygen in the overlying bottom water, no apparent macrofaunal life, and methane gas present in the sediment. High OSI values are given to aerobic bottom sediments with a deep apparent RPD, mature macrofaunal community, and no methane gas. Parameters for the OSI are measured visually from the REMOTS® images. The numerical values and ranges used in calculating the OSI are provided in Table 1.

Table 1. Calculation of the Organism-Sediment Index.

Choose One Value:		
	Mean RPD Depth Classes	Index Value
	0.00 cm	0
	> 0–0.75 cm	1
	0.76–1.50 cm	2
	1.51–2.25 cm	3
	2.26–3.00 cm	4
	3.01–3.75 cm	5
	> 3.75 cm	6
Choose One Value:		
	Successional Stage	Index Value
	Azoic	– 4
	Stage I	1
	Stage I–II	2
	Stage II	3
	Stage II–III	4
	Stage III	5
	Stage I on III	5
	Stage II on III	5
Choose One or Both if Appropriate:		
	Chemical Parameters	Index Value
	Methane Present	– 2
	No/Low Dissolved Oxygen	– 4
Organism-Sediment Index =		Range: –10 + 11

Results

Following completion of the East Harbor sediment cap in March 1994, a post-placement bathymetric survey and REMOTS® survey were conducted to document conditions of the completed cap. Results from these surveys provide a baseline comparator for assessing the long-term physical stability of the cap. In addition, biological parameters measured during the post-placement REMOTS® survey provide a benchmark from which benthic colonization of the sediment cap can be measured.

Two monitoring events have been conducted as part of the long-term monitoring of the East Harbor sediment cap. Monitoring one year after completion of the cap occurred in the fall of 1995; monitoring three years after completion of the cap occurred in the summer of 1997. Bathymetric surveys and REMOTS® photography surveys were conducted in both monitoring years. However, the 1995 bathymetric survey was conducted by the National Oceanic and Atmospheric Administration (NOAA) as

part of the navigational charting program. Data densities for the NOAA survey and the 1994 post-placement bathymetric survey were found to be incompatible, so a comparison between the surveys could not be made. All other monitoring data (bathymetry and REMOTS®) could be compared to the post-placement survey data to assess physical stability of the cap.

Physical Stability of the East Harbor Cap

REMOTS® survey results indicate a slight eastward shift of the northeastern perimeter of the cap, but significant changes in the overall distribution of cap material has not occurred since cap placement (Figure 4). Cap material was identified in REMOTS® images by its optical contrast to native sediments. Cap sediments are composed primarily of tan to gray, poorly sorted sands with woody debris, and native sediments are generally composed of tan, well-sorted sands or silts. Cap material visible in 1995 along the eastern cap perimeter is absent in 1997. The apparent loss of cap material is likely due to biological mixing of sediments. Over time, the optical distinction between cap material and native sediments will be obscured by sediment bioturbation.

Results of the 1997 bathymetric survey were compared with those of the 1994 post-placement survey to determine whether changes have occurred in areas where cap thickness was greater than one foot (>30 cm). Cross-sections of the 1997 survey were made in areas most likely to show evidence of changes in cap thickness and compared to the same cross-sections from the 1994 post-placement survey (Figure 5). With the exception of Zone A, cross-section comparisons of the bathymetric data suggest that cap thickness has not changed significantly.

Cross-section A-A' (Figure 6) begins at the ferry terminal and runs due east toward the outer harbor. The cross-section data shows that approximately 40 cm (1.3 ft) of material has been lost in the scour zone since placement of the cap. Loss of cap material was also evident in this area during the 1995 REMOTS® survey. Along the eastern portion of the transect, where the harbor bottom transitions to the outer harbor, the 1997 survey shows approximately 22 cm (0.7 ft) of material accumulation. Cross-section B-B' (Figure 7) is oriented north-south across the eastern portion of the cap. The cross-section data show no significant difference between the two surveys. The apparent accumulation of material along the northern part of the cross-section is less than 15 cm (<0.5 ft). Cross-section C-C' (Figure 8) begins in the southwest corner of the cap and crosses northeast to the edge of the cap. The cross-section data show no significant changes in the southern portion of the cap. The northern portion of the cap also appears unchanged, with the exception of the cap material mounds. During cap construction, mounds of cap material were created in the northern portion of the cap when portions of the cap material load would "hang up" in the split-hull barge and then rapidly exit in a clump (U.S. EPA et al., 1994). A cap material mound visible in cross-section C-C' shows evidence of smoothing since cap placement.

Depth differences of ±1 ft (±30 cm) or more measured between the 1994 and 1997 surveys are contoured and plotted in Figure 9. Cap sediments have been eroded in some areas of Zone A, but have also been re-deposited within Zone A. In the eastern portion of the cap, Zone E and parts of Zone D appear to show some areas (diameter of 50 to 100 ft [15 to 30 m]) with cap material loss up to 2 ft (60 cm). This represents approximately 2200 m^3 of material, or 1.0 % of the total volume of cap material (211,000 m^3) placed in Eagle Harbor. However, the apparent loss of cap material in Zone E is not corroborated by the REMOTS® data. Sediment accumulation mounds recorded in the southern portion of the cap are bathymetric survey artifacts; barges and vessels anchored in the southern cap area during the 1997 bathymetric survey prevented the survey vessel from reaching those areas.

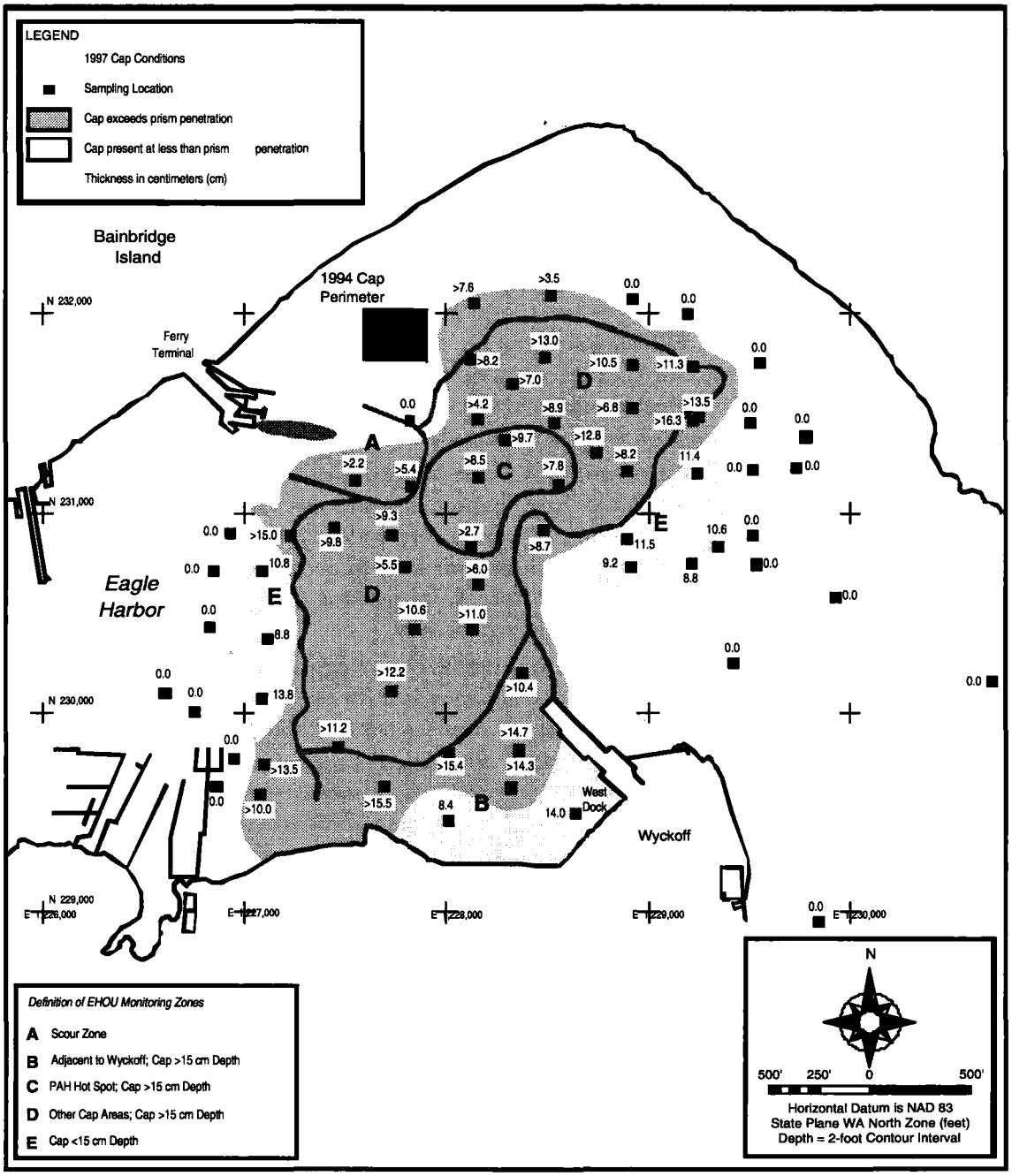

Figure 4. Cap material distribution on REMOSAE surveys conducted of the East Harbor cap.

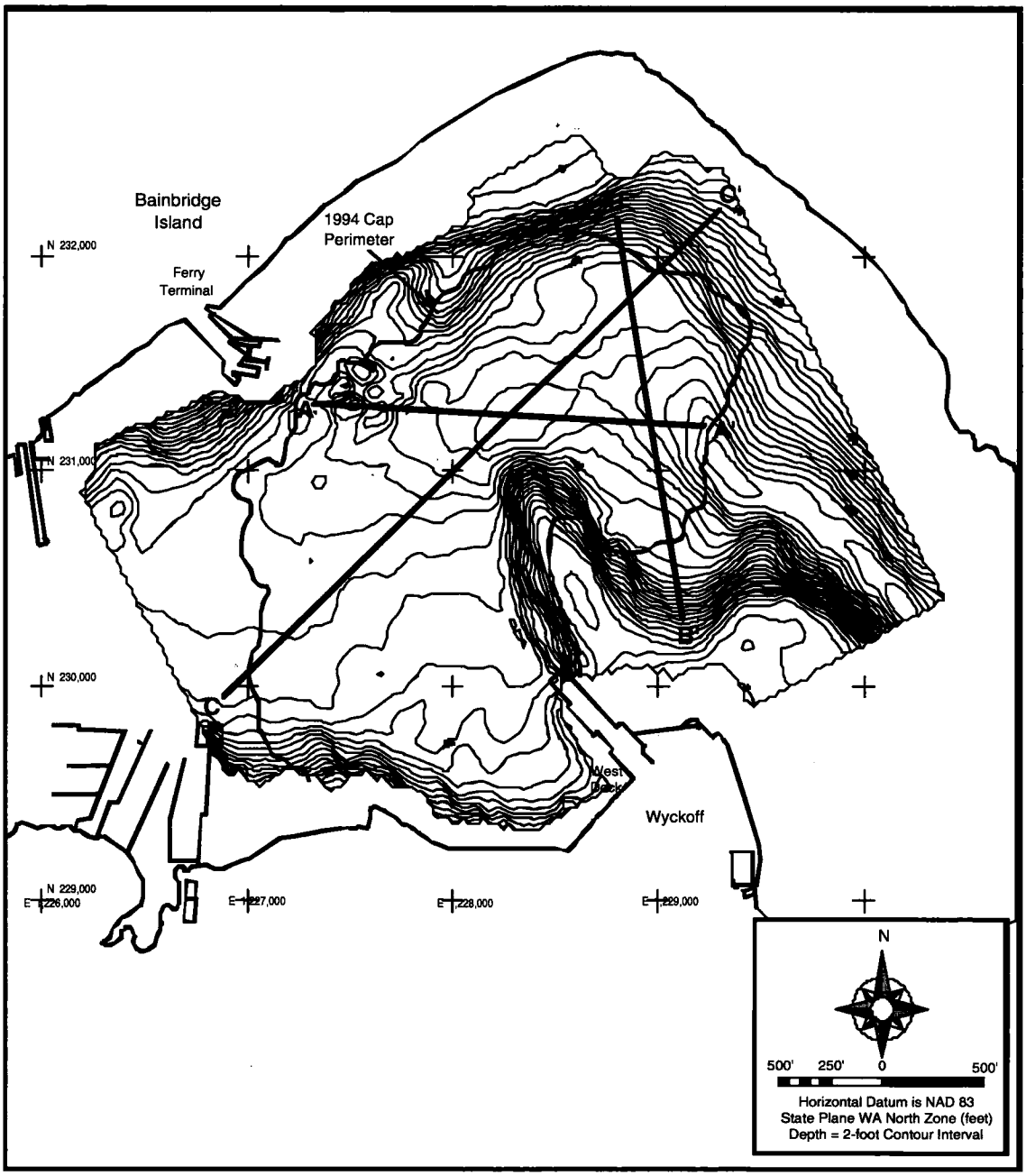

Figure 5. Eagle Harbor 1997 bathymetry survey and cross sections for comparison to the 1994 post-placement survey.

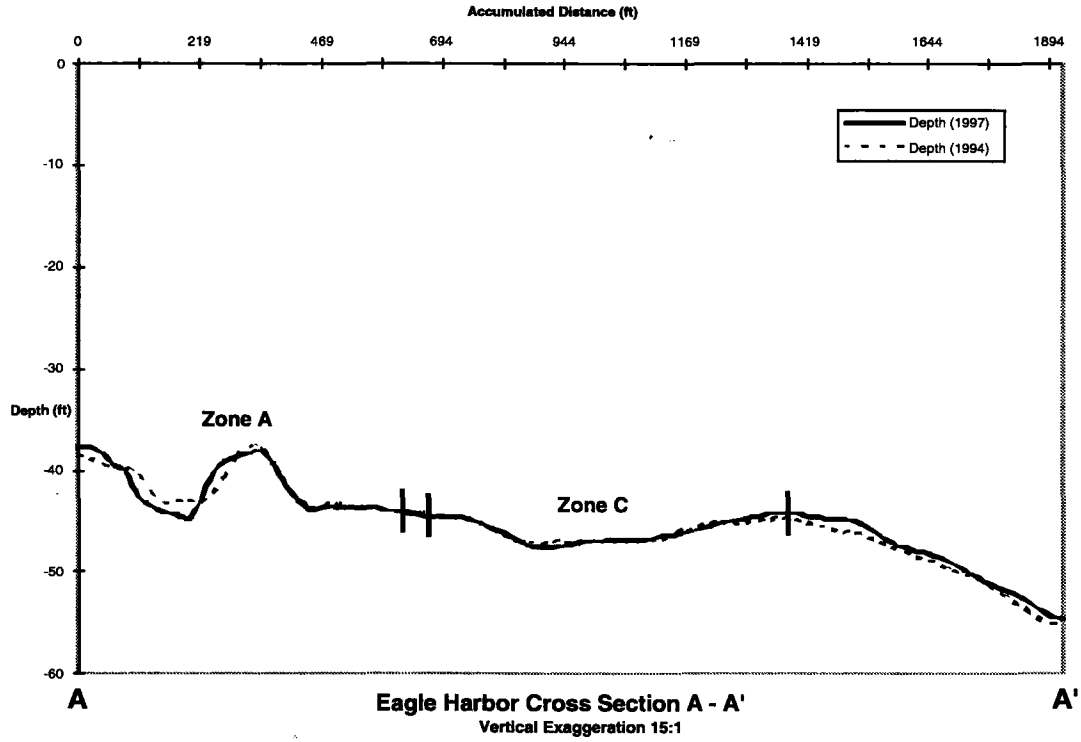

Figure 6. Cross section A-A'. 1994 and 1997 bathymetric data.

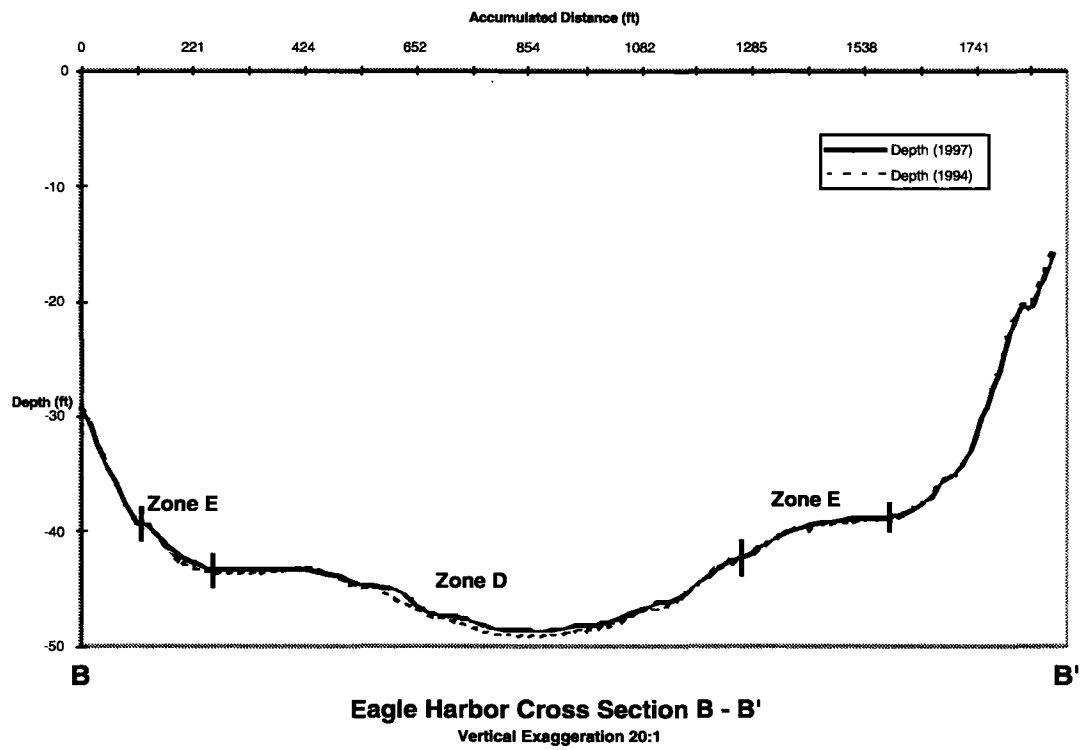

Figure 7. Cross section B-B'. 1994 and 1997 bathymetric data.

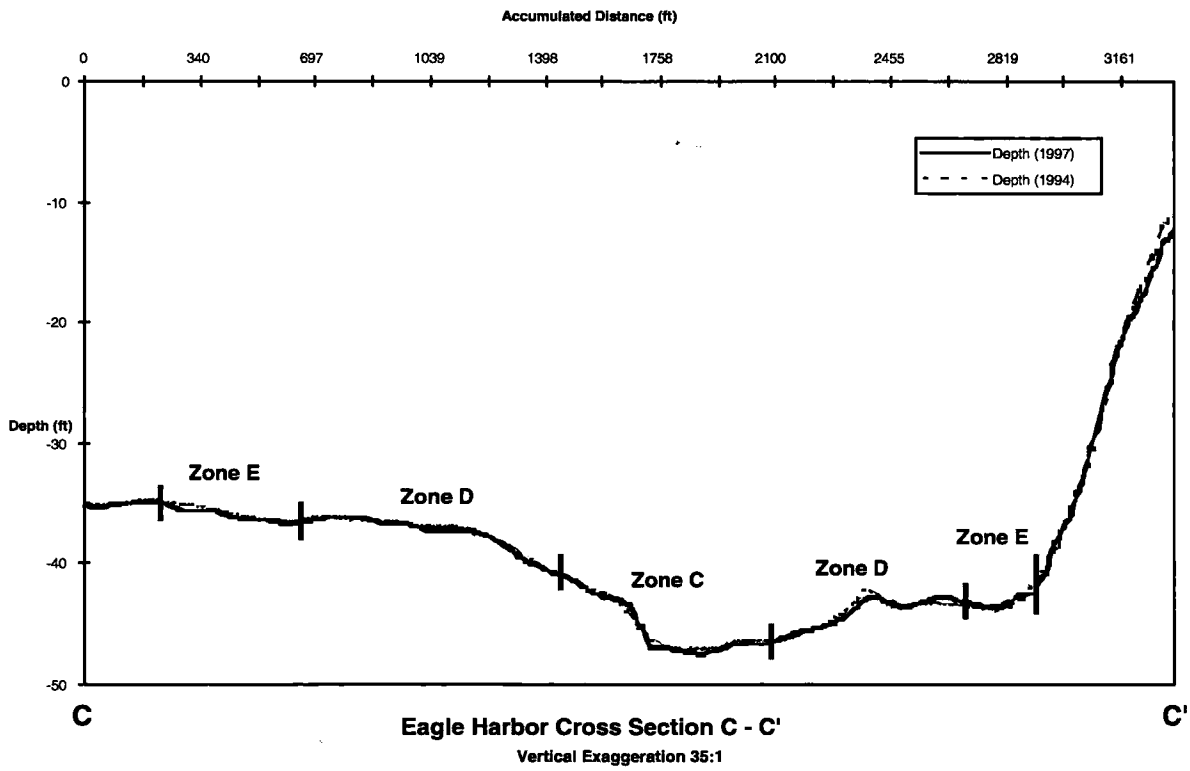

Figure 8. Cross section C-C'. 1994 and 1997 bathymetric data.

Benthic Colonization of the Cap

REMOTS® images were analyzed for the RPD depth, infaunal successional stage (the functional type of infaunal organisms present), the presence of methane, and the presence of oxic or anoxic sediments to assess benthic infaunal colonization. These parameters are used to calculate OSI values, which provide a general indicator of cap sediment habitat quality for the colonizing benthic infauna.

Mean RPD depths have increased over time in most areas of the East Harbor OU cap, suggesting increased levels of sediment bioturbation by the benthic infauna. During the post-placement survey in 1994, the mean for all RPD depths was 2.49 cm. In 1997, the mean for all RPD depths had increased to 3.28 cm. Infaunal successional stages present on the cap are also transitioning to Stage III communities. In 1997, Stage III infauna (long-lived successional stages) were observed in the northern and southern portions of the cap, and at two stations in the central cap region. The frequency of Stage III classifications has increased since cap placement, from 25% of all stations during the 1995 survey to 38% during the 1997 survey. OSI values for the East Harbor sediment cap have thus improved since cap placement, suggesting that cap sediments are providing suitable habitat for benthic infauna (Figure 10). Following construction of the cap in 1994, the median OSI value was 5. The median OSI value was also 5 during the year-one survey in 1995, but had increased to 7 during the year-three survey.

Discussion

The distribution of the East Harbor sediment cap remains generally unchanged based on REMOTS ® measurements. However, small changes in the cap perimeter have been observed over time and can be attributed to variable redistribution of the cap material and bioturbation of the cap material with the ambient sediments. In the future, cap sediments at the margins of the cap will be well bioturbated with the native sediments, at which time sediment profile photography will no longer be able to visually distinguish thin capped areas (Zone E) from the ambient bottom sediments.

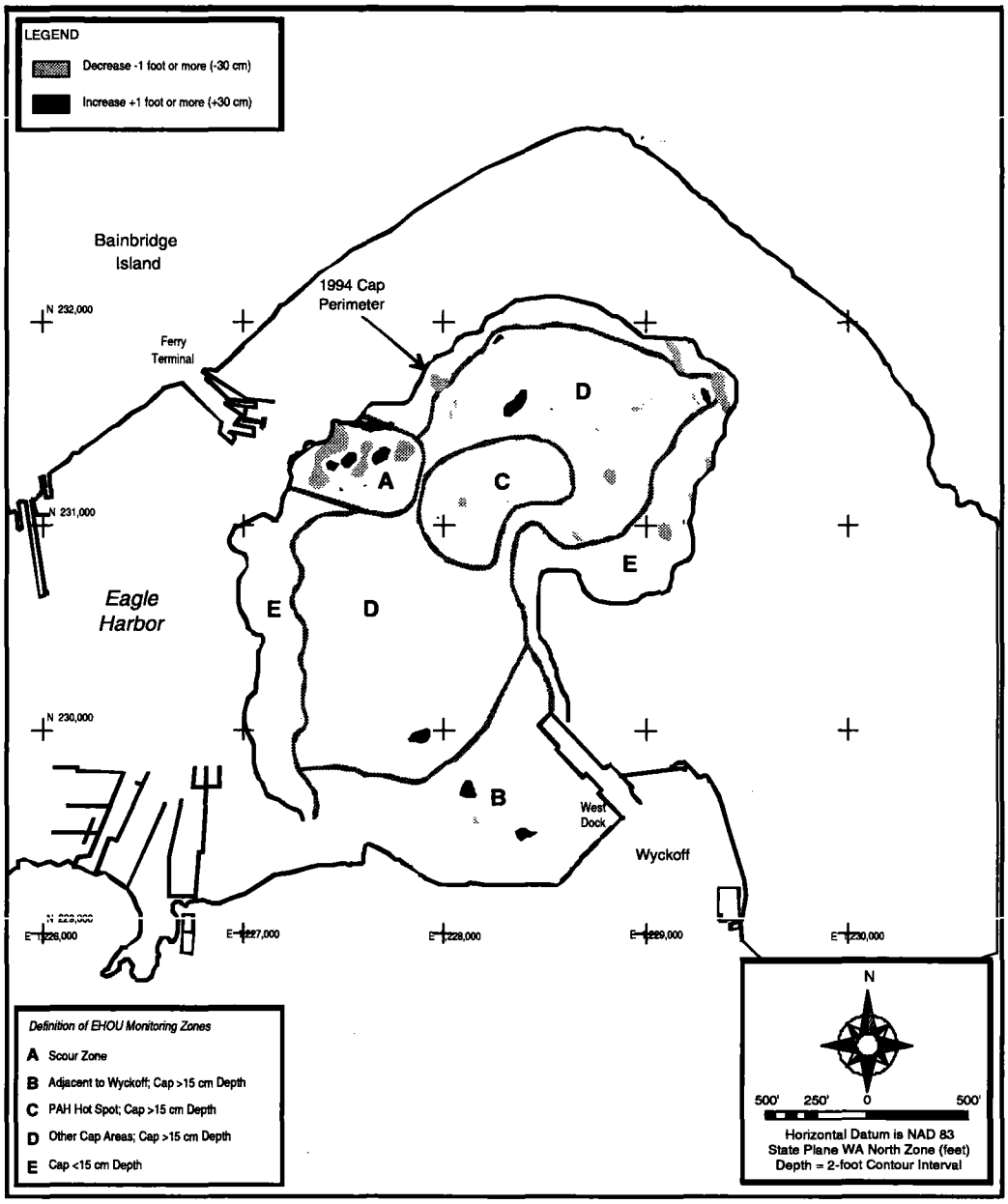

Figure 9. Depth differences greater than 1 ft (<30 cm) between 1994 and 1997 surveys.

Comparison of bathymetric surveys conducted in Eagle Harbor indicates very little change in the thickness of the cap (no greater than 1 foot), except in areas where erosion was anticipated (Zone A). However, the smoothing of cap material mounds in the northern portion of the cap suggests that some localized movement or settling of cap sediments has occurred since the cap was completed. REMOTS® images were examined for grain-size major mode, sediment sorting (armoring or winnowing of fine-grained sediment), and development of physical surface-boundary roughness features (ripples or bedforms) to locate potential areas of sediment instability or erosion. A REMOTS® image showing evidence of physical boundary roughness is presented in Figure 11.

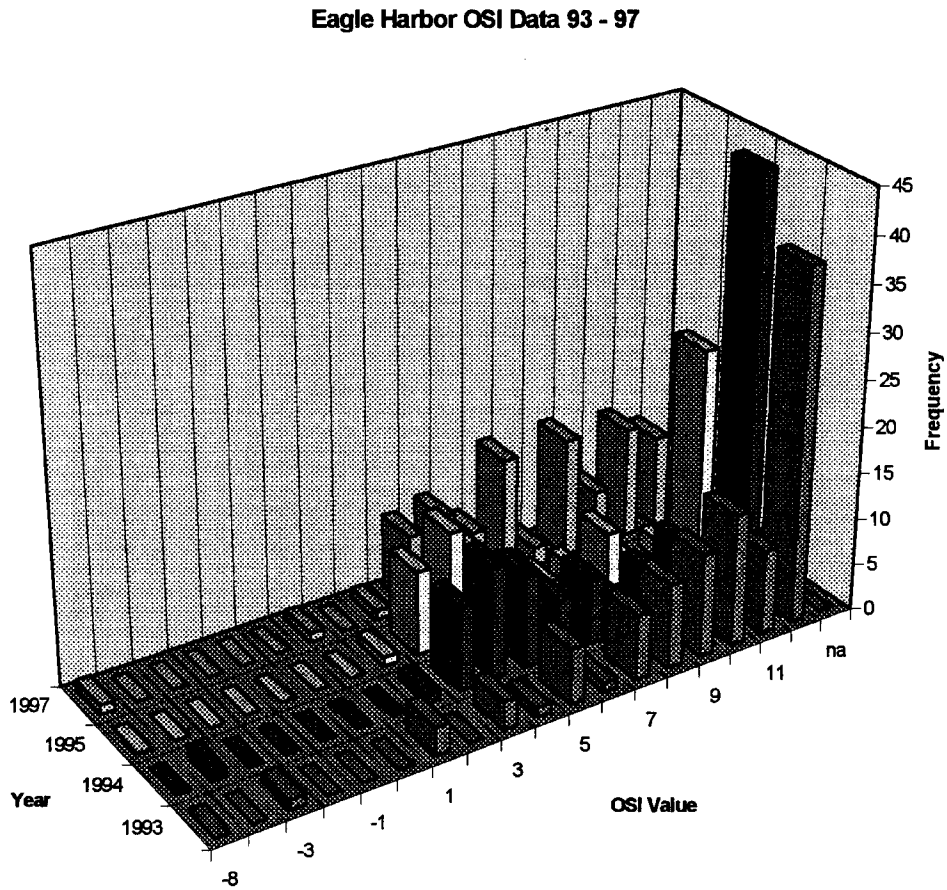

Figure 10. Frequency of Organism-Sediment Index (OSI) values measured at the East Harbor OU sediment cap.

Sediment grain-size measured in areas affected by ferry propeller wash reflect conditions where cap sediments have been winnowed of fine-grained material, or eroded away. Cap sediments are composed mostly of fine sands (4–3 phi). In much of Zone A and the surrounding regions of Zone C and D, medium sands (3–2 phi) are now present. Gravels (<–1 phi) are also present in Zone A, which clearly indicates erosion of cap material.

The area of the cap showing physically induced boundary roughness features due to ferry scour has increased over time. Areas showing physically induced boundary roughness features attributed to sediment resuspension or transport (ripples and sediment sorting) include Zone A (scour zone), the surrounding regions in Zones C and D, and parts of Zone E (Figure 12). Although the cap area showing physical boundary roughness has increased, the magnitude of physical boundary roughness has not changed significantly. In 1997, physical boundary roughness values ranged from a low of 0.27 cm at the northern portion of the cap to a high of 3.46 cm in the ferry scour zone (Zone A). The range of boundary roughness values is higher in comparison with previous surveys. However, the mean boundary roughness value for the 1997 survey (0.95 cm) was not significantly higher than that for the 1995 survey (0.82 cm).

Conclusions

Repetitive bathymetric surveys in conjunction with REMOTS® sediment profile photography are an effective method for monitoring the long-term physical stability of the East Harbor OU sediment cap. Sediment grain-size and physical boundary roughness features measured in some areas of the cap, and smoothing of cap material mounds in the northern portion of the cap are evidence of the erosive

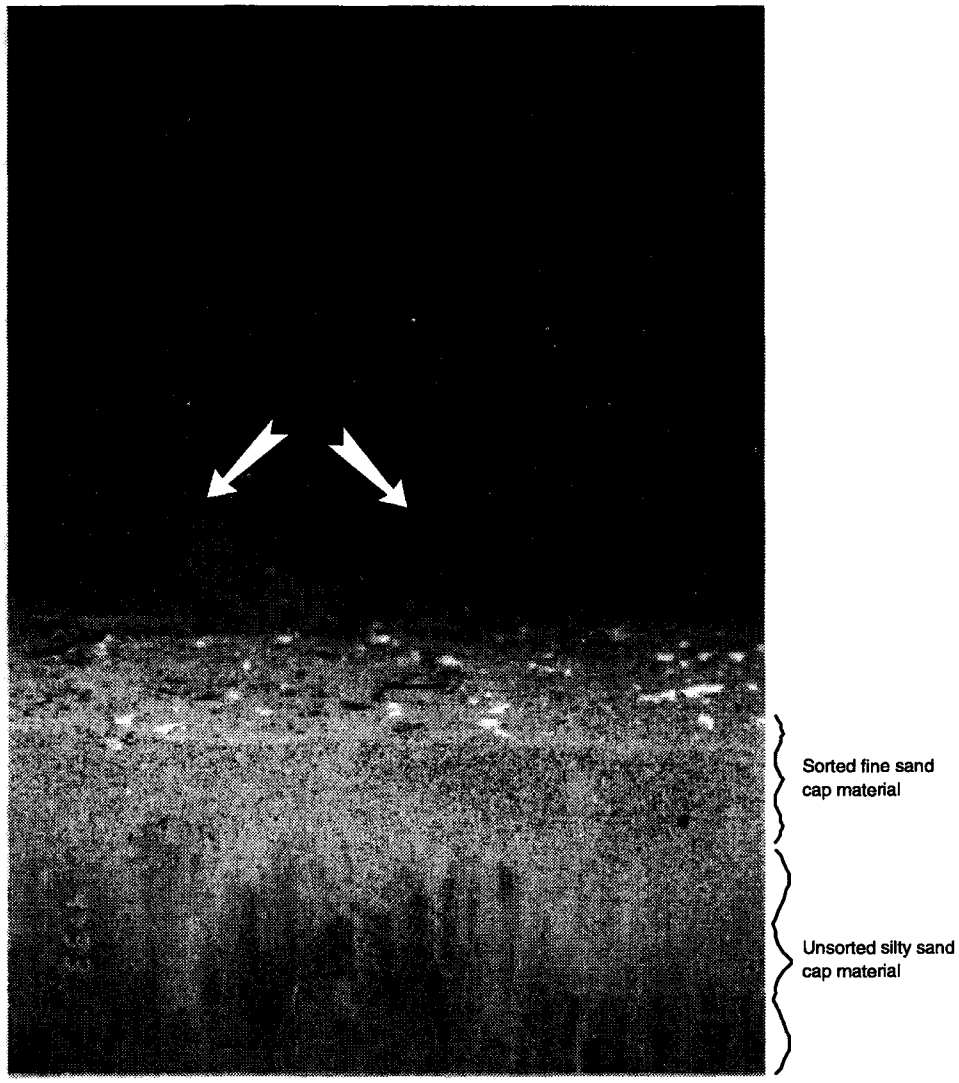

Figure 11. REMOSAE image from station T4-5 (Zone C) collected during the 1997 monitoring survey of the East Harbor. Station T4-5 is located just east of the scour zone perimeter (Zone A). Cap material is greater than prism penetration. The image shows approximately 2 cm of sorted fine sand overlying unsorted silty sand cap material. Shell, wood debris, and tubeworms (arrows) are on the surface. Image width is 15 cm.

force of ferry propeller wash. However, the repetitive bathymetric surveys conducted in Eagle Harbor suggest that significant changes in cap thickness has not occurred, with the exception of Zone A (Figure 9). Some areas surrounding Zone A have likely experienced cap erosion, but not greater than one foot (bathymetric survey threshold). It is possible that cap sediments where fine-grained sediments have been winnowed away may become armored, thus increasing cap stability in those areas. Cap areas showing physical boundary roughness features (sediment sorting, ripples, or bedforms) should be considered areas of potential cap erosion and should be closely monitored. Repetitive bathymetric surveys conducted as part of the long-term monitoring can identify cap regions where significant cap erosion is occurring.

Acknowledgments

The authors wish to acknowledge Ms. Sandy Browning and Mr. David Browning for their contributions during cap construction monitoring and post-placement monitoring of the East

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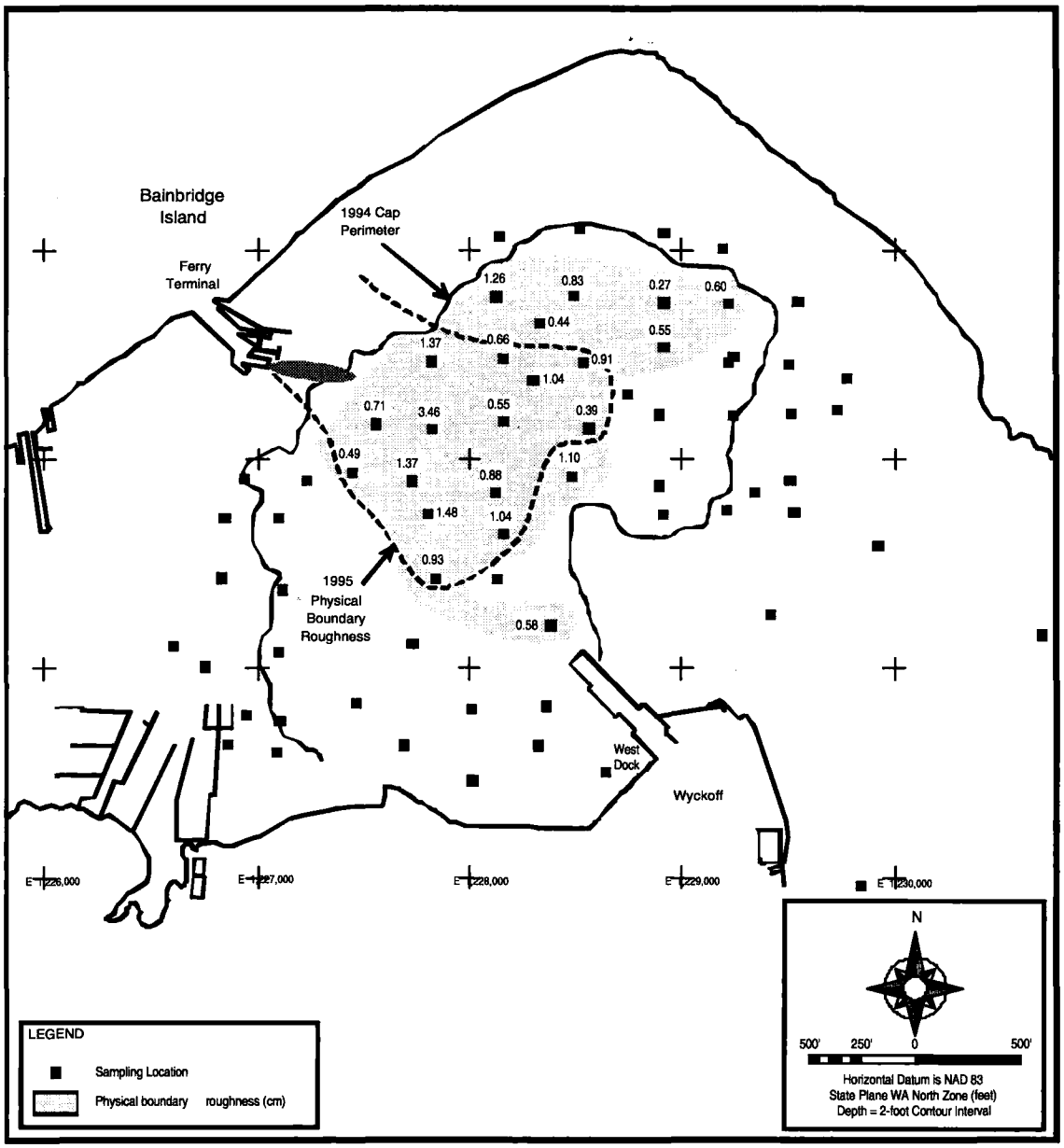

Figure 12. Physical boundary roughness attributed to sediment resuspension and transport based on the 1997 REMOSAE data.

Evidence of sediment cap colonization by benthic organisms provides a general indication of whether the cap is providing clean, suitable habitat. Organism-sediment index (OSI) values calculated from on-cap REMOTS® images suggest that cap sediments are providing suitable habitat for benthic infauna. Redox potential discontinuity (RPD) depths, which indicate the depth of biological activity, have increased since cap placement. Stage III infauna, whose presence indicate ongoing ecological succession, continue to colonize most regions of the cap.

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Bellingham Bay Demonstration Pilot

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Introduction

This paper presents an update on the status of the Bellingham Bay Demonstration Pilot (Pilot). The first section provides background information on the Pilot and its objectives. The next section presents the approach being used including what will be accomplished, the regulatory framework for documenting the work, and the process that has been followed. The third section presents the current status of the project and summarizes the major findings made to date. The final section describes the next steps in the Pilot.

Background and Objectives

In 1996, a group of six state and federal agencies formed the Cooperative Sediment Management Program (CSMP) to address the need for sediment cleanup and overcome some of the existing roadblocks to expedited action. The CSMP agencies include:

- Washington Department of Ecology;
- U.S. Army Corps of Engineers;
- Washington State Department of Transportation;
- U.S. Environmental Protection Agency;
- Washington State Department of Natural Resources;
- Puget Sound Water Quality Action Team.

These agencies developed a demonstration pilot concept that was designed to have federal and state agencies working cooperatively with local government and businesses to collectively address sediment problems in Puget Sound's urban bays. The Pilot is funded by the Department of Ecology's Local Toxics Control Account established through the Model Toxics Control Act (MTCA).

In June 1996, following discussions with interested parties from four urban bays in Puget Sound, Bellingham Bay was selected as the location for the CSMP's demonstration pilot. Bellingham Bay was selected in part due to the responsiveness of a local group describing collaborative efforts already underway. This group included the Port of Bellingham, City of Bellingham, Whatcom County Health Department, and Georgia-Pacific West, Inc. The local group emphasized the need to focus on practical, cost-effective approaches to sediment management that could provide both environmental and economic improvements to the local community. The Pilot was seen as an opportunity to evaluate the potential for achieving multiple objectives in Bellingham Bay through comprehensive strategic environmental planning and well-integrated projects that would encompass contaminated sediment cleanup, sediment disposal, habitat restoration, source control, and shoreline property management. The Pilot was initiated in the fall of 1996 with the establishment of the Bellingham Bay Work Group (BBWG). The BBWG includes representatives from:

- Washington Department of Ecology;
- Washington State Department of Natural Resources;

- Washington State Department of Transportation;
- U.S. Army Corps of Engineers;
- Port of Bellingham;
- City of Bellingham;
- Whatcom County Health Department;
- Georgia-Pacific West, Inc.;
- Washington Department of Fish and Wildlife;
- U.S. Fish and Wildlife Service;
- U.S. Environmental Protection Agency;
- Puget Sound Water Quality Action Team;
- Huxley Environmental College;
- Nooksack Tribe;
- Lummi Nation.

The BBWG first established a consensus-based decision making framework, identified the geographic scope of the project as being all of Bellingham Bay from Governor's Point to Portage Island (Figure 1), and confirmed a focus on toxic substances rather than conventional pollutants. A mission statement, objectives, and a draft scope of work to meet those objectives were then developed. In April of 1997, a consultant team was selected to implement the scope with BBWG oversight.

Pilot Mission and Objectives

Consistent with the intent of the CSMP, the BBWG developed the following mission statement for the Pilot: "Use a new cooperative approach to expedite source control, sediment cleanup and associated habitat restoration in Bellingham Bay."

To achieve this mission the BBWG developed broad objectives falling into three categories as listed below:

Environmental Objectives

- Implement a thoughtful planning approach for integrated environmental actions within Bellingham Bay, including source control, sediment cleanup and protection of aquatic resources;
- Prioritize and take early action on contaminated sediment sites that pose a threat to public health and the environment in the bay. Specific examples include:
    - Whatcom Waterway MTCA Site;
    - Cornwall Avenue Landfill MTCA Site;
    - Harris Avenue Shipyard MTCA Site.
- Design and permit a multi-user disposal site for contaminated sediments associated with priority problem areas.

Process Objectives

- Build a comprehensive record of existing environmental and land use information to support planning efforts in Bellingham Bay.
- Develop and utilize a coordinated regulatory process to provide more streamlined and predictable permitting, design and implementation of priority projects.
- Consider a reasonable range of alternatives for sediment remediation that are protective, cost-effective and practicable within an urban embayment.

- Maintain coordination with other sources of emerging information regarding sediment remediation and habitat mitigation.
- Provide for effective integration of environmental remediation with economic development, including cleanup and redevelopment of contaminated property, coordination of project timelines to achieve multiple objectives, and maintaining flexibility for individual landowners.

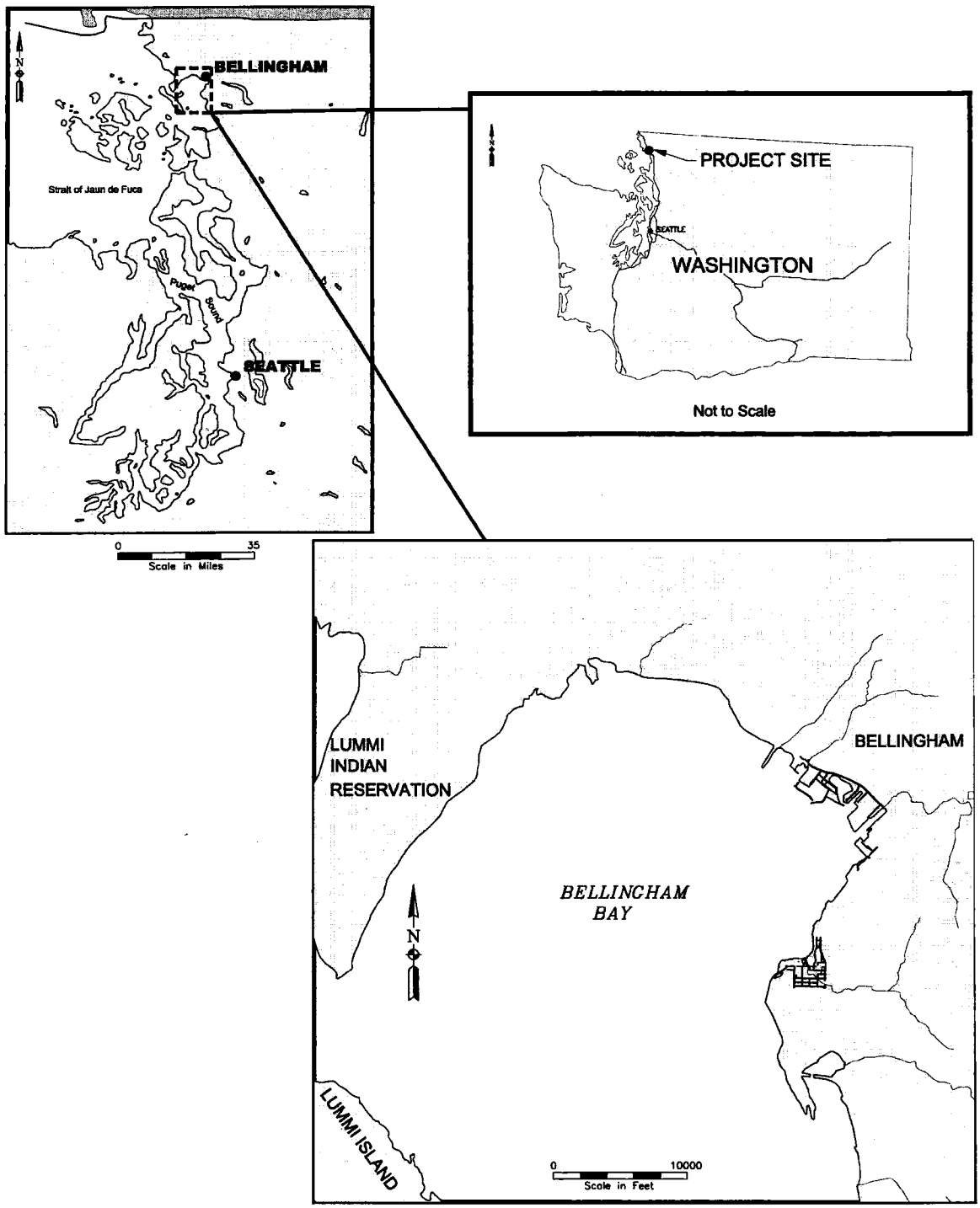

Figure 1. Vicinity map, project area.

Partnering Objectives

- Develop a framework for sediment remediation that is among cooperative partners, environmentally protective, cost-effective and practicable within the urbanized portion of Bellingham Bay.
- Maintain an effective working relationship among project participants by:
    - ensuring federal, state, tribal and local participation;
    - providing a forum for cooperative, consensus-based decision-making;
    - utilizing local expertise and resources as much as possible;
    - identifying and implementing means of broad public participation;
    - allowing for future expansion of the current work group as appropriate.
- Identify and coordinate public and private opportunities for project participation and funding, including a framework for project cost sharing.
- Provide for cooperative resolution of liability for historical environmental problems associated with contaminated marine sediments with less litigation, less administrative redundancy, and less project delay.
- Document elements of the Pilot that may be transferable to other locations.

Overall Approach—Methods

The objectives of the Pilot represent a unique and comprehensive approach for achieving environmental results that are as efficient, effective, and as well-balanced as possible. To meet these broad objectives five project elements were identified, as well as the need for both short-term actions and planning for long-term actions. The five project elements are sediment cleanup, sediment disposal siting, source control, habitat restoration, and aquatic land use. To set priorities within each of these elements, brief goal statements reflecting the collective interests of the BBWG were developed. Once priorities were identified they were integrated into project alternatives to be implemented in the short-term. Priorities not included in the project alternatives will be carried forward in planning documents for future implementation. Determining the appropriate regulatory framework to document this work, and developing an effective prioritization process were key issues for the Pilot.

Regulatory Framework

A State Environmental Policy Act (SEPA) environmental impact statement (EIS) will be the primary work product of the Pilot. The EIS will document the Pilot process, evaluate the project alternatives for short-term actions that have been crafted from integrating priorities within each project element, and will contain planning documents to guide long-term actions. The EIS will also satisfy the project-specific SEPA requirements for individual sediment-cleanup sites addressed in the project alternatives.

Beyond the project-oriented alternatives, the EIS will also include planning documents as appendices. These will include the Remedial Action Plan, Habitat Restoration Plan, and Aquatic Land Use Plan. These "plans" will document the BBWG's vision of the future, but will not be binding. If any of the actions identified in the plans are implemented in the future, they will undergo their own environmental review. However, the Bellingham Bay Demonstration Pilot EIS could be used as the basis for their analysis. The EIS is expected to streamline the regulatory process, the coordination of public involvement, and the negotiation of cost sharing among parties for both short and long term actions.

Pilot Process

The Pilot needed a process to identify priorities within each of the project elements since the integration of these determines the short-term actions that will be taken. The elements that have been defined in the Pilot are sediment cleanup, sediment disposal, source control, habitat restoration, and aquatic land use. In each case, priority project actions will be included within the short-term alternatives in the EIS, and long-term project elements will be addressed in attached planning documents. For example, priority sediment sites will be targeted for expedited cleanup and included in the project alternatives, and other sites will be carried into the Remedial Action Plan to be addressed in the future.

Pilot success depends on integrating multiple priorities into project alternatives that can be implemented in the short term. An ongoing challenge has been to ensure that the various interests represented by the BBWG members are both understood and reflected in a well balanced process. The framework that has been developed to guide the Pilot is depicted in Figure 2. The process was not well developed at the onset of the project, but through adaptive management, an approach that identifies and integrates priorities was developed. The chart depicts the method used by the Pilot to develop priorities within each element and integrate them into project alternatives for evaluation in the EIS.

Existing data were compiled and evaluated for each project element and brought forward into element specific subcommittees comprised of BBWG members with expertise and interest. To prioritize the lists of information generated from this exercise, the BBWG defined a set of comprehensive goals, which were then transformed into evaluation criteria and scoring guidelines by the subcommittees. This work has been completed and the BBWG is currently going through the final step, integrating priorities into project alternatives, before initiating the EIS.

Pilot Status

Goals, Evaluation Criteria and Scoring Guidelines

Development of goals was an exercise in multiple stakeholder decision making, with each BBWG member contributing to defining the goals. Through this exercise, seven broad goals were defined and categorized as primary or secondary goals:

Primary Goals:

1. Human Health and Safety—implement actions that will enhance the protection of human health.
2. Ecological Health—implement actions that will protect and improve the ecological health of the bay.
3. Protect and Restore Ecosystems—implement actions that will protect, restore, or enhance habitat components making up the bay's ecosystem.

Secondary Goals:

4. Social and Cultural Uses—implement actions that are consistent with or enhance cultural and social uses in the bay and surrounding vicinity.
5. Resource Management—maximize material re-use in implementing sediment cleanup actions, minimize the use of renewable resources, and take advantage of existing infrastructure where possible instead of creating new infrastructure.
6. Faster, Better, Cheaper—implement actions that are more expedient and more cost effective, through approaches that achieve multiple objectives.
7. Economic Vitality—implement actions that enhance water dependent uses of commercial shoreline property.

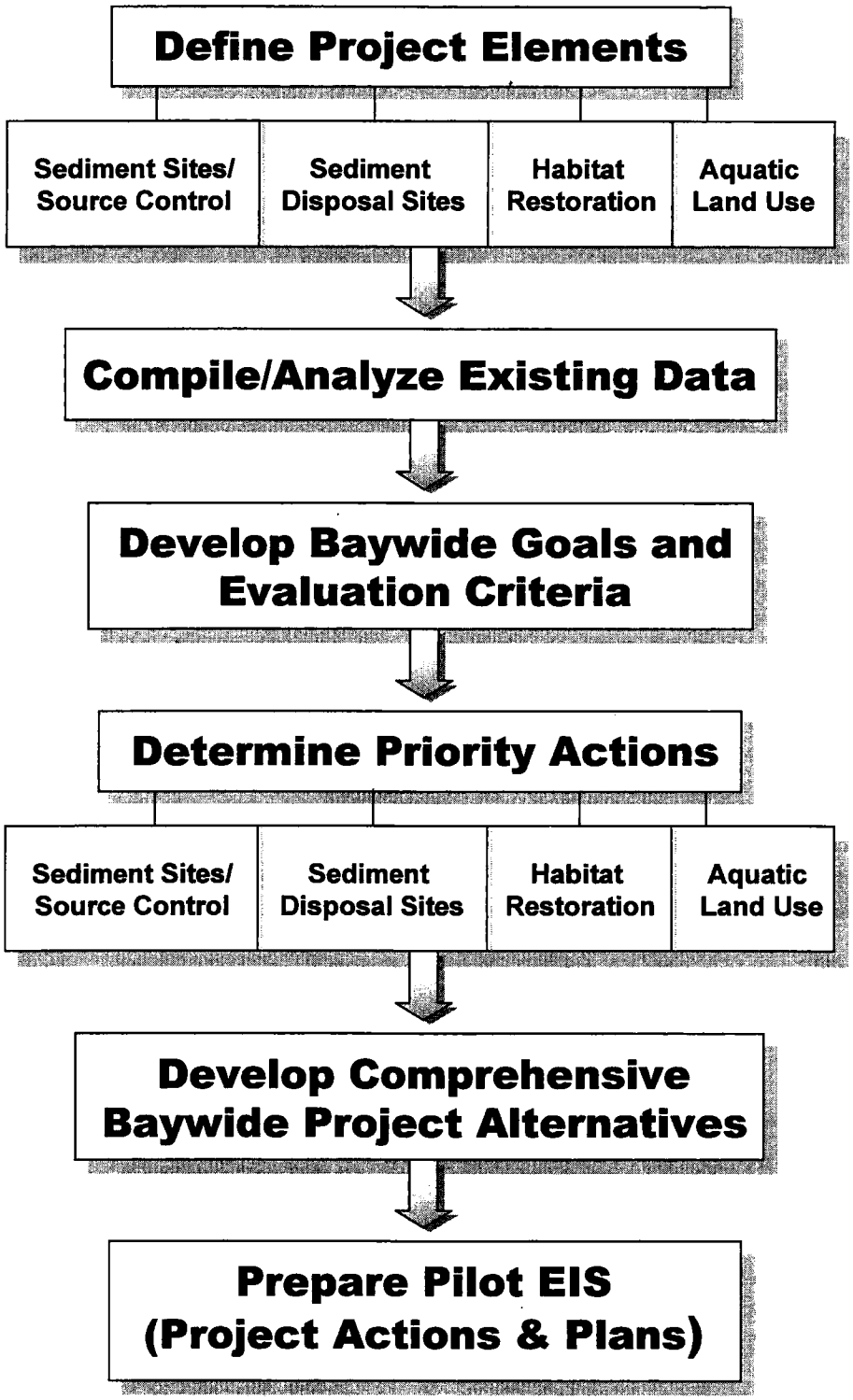

Figure 2. Overview of pilot process for determining priorities and developing project alternatives.

After the goals were developed, evaluation criteria were used to identify priorities within a given element. The evaluation criteria were developed in two sequential steps. First, a narrative description of each goal was prepared that defined the goal in the context of a specific element. Second, evaluation criteria with scoring guidelines were developed consistent with the narrative description of the goal. A numerical rating scheme (high = 5; low = 1) compared how well criteria were met. The scores from applying each criterion for any one goal were then summed and averaged to get an average score for each goal. Scores for all goals were then summed to get a total score. These total scores were compared and used to determine priorities.

Priorities

The preliminary results of prioritization within each element follow. The BBWG will finalize the results following review and comment on draft element-specific reports that are currently being written.

Disposal Sites

Identifying viable contaminated sediment disposal sites has been a challenge in virtually all of the urbanized bays in Puget Sound. In the Pilot, upland, nearshore, and confined aquatic disposal sites (CAD) were considered. The disposal site identification process included developing exclusionary and avoidance criteria as a screening step in the process, and then, similar to the other project elements, applying evaluation criteria and scoring guidelines to determine the final list of priorities. The exclusionary criteria were developed based on previous work from the Puget Sound Multi-user Disposal Siting report (PTI 1996) and Ecology's Recommended Standards for Confined Sediment Disposal (Ecology 1990). The exclusionary and avoidance criteria are provided in the Pilot's Draft Disposal Site Identification Report (Anchor Environmental LLC et al. 1998). Sixty-eight prospective sites were identified using these criteria. Of these 68, 36 were upland, 15 nearshore, and 17 were CAD sites. The 68 prospective sites were narrowed to a final list of eight sites by applying evaluation criteria and scoring guidelines derived from the seven goals of the BBWG. The evaluation criteria developed for disposal siting are provided as an example of what the evaluation criteria include, and are summarized in Table 1.

Table 1. Disposal sites—summary of evaluation criteria.

Goal	Criterion
1. Human Health and Safety	1A. Number of times the sediment has to be handled after dredging.
	1B. Short-term human exposure (risk of accident or release).
	1C. Long-term human exposure (risk of failure of engineered containment system).
	1D. Is disposal site an identified or suspected contaminated site from a human health perspective?
	1E. Would disposal control sources to sediments or water pose a human health concern?
2. Ecological Health	2A. Number of times the sediment has to be handled after dredging.
	2B. Short-term ecological exposure (risk of accident or release).
	2C. Long-term ecological exposure (risk of failure of engineered containment system).
	2D. Is disposal site an identified or suspected contaminated site from an ecological perspective?
	2E. Would disposal control sources to sediments or water pose an ecological health concern?
3. Protect/Restore Ecosystems	3A. Quality of existing habitat.
	3B. Restoration time frame.
	3C. Long-term quality and stability of final restored habitat.
	3D. Additional opportunity for protection or enhancement.
	3E. Adverse impacts to sediment deposition/transport.

Table 1. (continued)

Goal	Criterion
4. Social and Cultural Uses	4A. Current cultural/social use of disposal site area.
	4B. Long-term social/cultural uses following disposal; site compatibility with land use plans.
	4C. Additional opportunity for social/cultural uses.
5. Resource Management	5A. Potential reuse or conservation of renewable resources.
	5B. Adequacy of existing infrastructure to utilize resources.
6. Faster, Better, Cheaper	6A. Integrated land use and environmental objectives.
	6B. Adequacy of existing infrastructure.
	6C. Relative site cost.
7. Economic Vitality	7A. Water-dependent commerce/navigation.
	7B. Tribal economy.
	7C. Facilitates property redevelopment and economic vitality?

Application of evaluation criteria for the first three primary goals to the 68 disposal sites resulted in 21 sites being identified for further evaluation. The remaining 21 sites were evaluated using the secondary goals and their criteria, and the results of that evaluation led to the following priority disposal sites.

Upland Sites:	Nearshore Sites:	CAD Sites:
Tulalip Landfill	Cornwall Avenue Landfill	Cornwall Avenue Landfill
Phyllite Quarry	Georgia-Pacific Log Pond	Georgia-Pacific ASB
Roosevelt Landfill		Inner Bellingham Bay

These eight priority sites:

- scored the highest among all disposal sites evaluated within a given disposal environment (i.e., upland, nearshore, or CAD);
- had confirmation with current owners that the site was available for disposal subject to future negotiated agreements pertaining to cost, schedule, and other considerations;
- had a minimum disposal capacity of 100,000 c.y.;
- for most of the CAD and nearshore sites accomplished multiple objectives by locating the disposal site over a contaminated sediment site; and
- will be carried forward into the element integration exercise.

Sediment Sites

Prospective sediment cleanup sites were identified from the existing SEDQUAL database maintained by Ecology, data from the ongoing Whatcom Waterway and Cornwall Avenue Landfill investigations, and other available data. Prospective cleanup sites were identified using Ecology's Contaminated Sediment Site Listing methodology, which defines a station cluster of potential concern. This exercise resulted in 10 areas of potential concern, including five known sites and five potential sites as defined by the state's guidelines for listing sites:

Known Sites:	Potential Sites:
Whatcom Waterway	Boulevard Park
Harris Avenue Shipyard	Inner Squalicum Harbor
Georgia-Pacific Outfall	Squalicum Shipyard
Cornwall Avenue Landfill	Taylor Avenue Docks
Olivine Nearshore Area	Weldcraft Steel & Marine

Using the evaluation criteria and scoring guidelines developed for this element, the prospective sites were ranked for priority to be integrated into the project alternatives. The five known sites were prioritized as follows:

High Priority Sites:	Medium Priority Sites:	Low Priority Sites:
Whatcom Waterway	Harris Avenue Shipyard	Olivine Nearshore Area
	Cornwall Avenue Landfill	Georgia-Pacific Outfall

All of the high and medium priority known sites will be carried forward into the element integration exercise. The low priority known sites and potential sites will be addressed in the Remedial Action Plan, a supporting document to the project EIS that will be developed as part of the Pilot.

The Whatcom Waterway site will be further separated into several sub-areas. The sub-areas will be used to separate those sediment sites where removal is the only remediation option, as opposed to other sites where natural recovery, capping, or other non-removal oriented remediation techniques are viable. One of the primary reasons for the further separation is the fact that some of the contamination areas in the Whatcom Waterway site include federally authorized navigation channels.

Habitat

The process to determine priority habitat actions began with a workshop. Interested work group members were invited to attend with the objective of identifying key species whose habitat warranted protection and restoration in Bellingham Bay. Following the workshop members of the subcommittee met to develop a vision for the overall habitat restoration for Bellingham Bay. The overall vision developed for the bay with respect to habitat is to maximize productivity to the extent possible by:

- cleaning up contaminated sediments;
- controlling point and non-point sources of contamination;
- containing or removing shoreline landfills;
- restoring viable estuaries (Squalicum, Whatcom, Padden, and Little Squalicum);
- maximizing shoreline riparian vegetation;
- removing shoreline fills that result in a net gain in in-water habitat;
- removing remnant in-water structures;
- removing/replacing creosote treated piles; and
- identifying opportunities for restoration/protection not necessarily associated with compensatory mitigation.

The species of interest identified for the bay include:

- five Pacific salmon species,
- Dolly Varden,
- cutthroat trout and steelhead,
- sand lance and surf smelt,
- Pacific herring,
- ling cod,
- pandalid shrimp,
- Dungeness crab,
- and hardshell clams.

Having developed a vision and identified key species, the next step was to inventory the bay for prospective habitat restoration/enhancement opportunities. Using existing data and site knowledge, members of the BBWG identified approximately 40 potential sites to restore/enhance habitat. The Pilot goals and evaluation criteria were then used to winnow these prospective sites down to a shorter list of priority actions. In developing the evaluation criteria for determining priority habitat actions, the habitat subcommittee chose to rearrange the Pilot goals in terms of which ones were primary and which ones were secondary. Since the purpose of this element was restoration, the "protect and restore ecosystems" goal was chosen as the primary goal, and the remaining six goals were viewed as secondary. Using the evaluation criteria developed for habitat, 15 priority habitat actions were identified. The actions include removing fill and converting it to salt marsh and/or mudflat, restoring shallow water habitats through elevation and substrate modifications, and modifying subtidal elevations to shallower water eel grass habitats. Many of the priority restoration actions serve to provide connectivity from the mouth of the urban streams through the industrialized shoreline areas to the less developed and more natural shoreline areas of the bay.

Source Control

One of the objectives of the Pilot is to control sources of water quality and sediment quality problems in Bellingham Bay. As the existing data were reviewed, it became apparent that hazardous substance discharges are not affecting the water quality of Bellingham Bay, but are having an adverse impact on sediments. Therefore, the source control subcommittee decided to control ongoing upland sources of hazardous substances in the areas with impacted sediments. As a result, controlling known and potential sources with sediment cleanup will be linked as described in Table 2.

Table 2. Summary of the linkage between sediment sites and sources.

Known Sediment Sites	Known Sources	Potential Sources
1. Whatcom Waterway	1a) G-P groundwater mercury discharges to log pond 1b) City storm drain phenol and 4-methylphenol discharges	1c) Localized wood waste inputs (deleterious substances)
2. Harris Avenue Shipyard		2a) Shipyard operation (NPDES) 2b) Groundwater discharges
3. Cornwall Avenue Landfill	3a) Shoreline erosion of metals and solid waste 3b) Groundwater discharges of metals (water-only concern)	
4. Olivine Nearshore Area		4a) Upland runoff 4b) City storm drain discharges 4c) Groundwater discharges
5. G-P Outfall		5a) Wastewater (NPDES)
Potential Sediment Sites	**Known Sources**	**Potential Sources**
6. Boulevard Park		6a) Upland runoff 6b) Groundwater discharges
7. Inner Squalicum Harbor		7a) Upland runoff 7b) Groundwater discharges
8. Squalicum Shipyard		8a) Shipyard operation 8b) Groundwater discharges
9. Taylor Avenue Docks		9a) Upland runoff 9b) Groundwater discharges
10. Weldcraft Steel & Marine		10a) Upland runoff 10b) Groundwater discharges

Given the close linkage between sediment sites and sources, the subcommittee decided it was not necessary to develop evaluation criteria to determine priority actions. The priority sources that will be addressed through the Pilot are reflected in the sediment cleanup priorities.

Aquatic land use

Integrating aquatic land use issues into sediment cleanup and habitat restoration is an important part of the Pilot. The mechanism for accomplishing this integration will be two-fold. First, priority land use actions will be integrated into the project alternatives along with priorities from the other project elements. Second, an Aquatic Land Use plan will be developed as part of the Pilot.

Evaluation criteria will not be developed to identify priority aquatic land use actions. Rather, the key decision-makers in shoreline uses and designations (i.e., the City, Port, and DNR), will identify priorities through their Shoreline Master Plan and Harbor Area Master Plan documents. Draft project alternatives will then be crafted to incorporate as many priority aquatic land use actions as possible while balancing sediment cleanup and habitat restoration. The draft project alternatives will also be evaluated to determine what future land use opportunities they provide. The outcome of that evaluation will be the basis for preparing the Aquatic Land Use Plan. This plan will serve to guide future aquatic land use decisions in Bellingham Bay and will be an appendix to the Pilot EIS (described previously). It is expected that updates to formal planning documents (e.g., SMP and Master Plans) will occur concurrently through separate but related actions by the Port or City.

Next Steps

The Pilot is currently completing the element integration exercise and developing project alternatives. A Purpose and Need Statement for use in the EIS is being finalized and all project alternatives carried forward to the EIS will be judged according to their ability to meet the purpose and need. The current schedule calls for EIS scoping in May 1998. The EIS and planning documents will be prepared at the same time immediately following scoping. As the alternatives are being evaluated, the Work Group will begin the process of selecting a preferred alternative, using the outcome of the SEPA EIS as one of the major factors in selecting a preferred alternative. A draft EIS is currently planned for fall of 1998; and a final EIS and project implementation activities in the spring of 1999.

Acknowledgements

The authors would like to thank the members of the Bellingham Bay Work Group for their continued hard work and cooperative spirit on the Pilot. In addition to the regular work group meetings, many members have provided additional time on various subcommittees. We would also like to thank the many other agency staff who, while not regular BBWG members, contributed their time and energy on specific tasks on the Pilot. In particular we would like to thank Dr. Teresa Michelsen for her creativity and contribution in providing the process framework for priority setting. Also, Tracey McKenzie and Clay Patmont, while not authors on this paper, certainly deserve much of the credit for the progress and results made to date on the Pilot.

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A Quantitative Geoacoustic Technique for Characterizing Marine Sediments

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Abstract

Cost-effective and rapid means of mapping the distribution of sediments in harbors and rivers are required to facilitate the remediation decisions facing environmental managers. One's ability to manage polluted environments effectively is in part a function of the accuracy of the available site-characterization data. In general, these data should provide accurate descriptions of the physical properties of the sediment,s along with delineation of the lateral and vertical extents of all unique sediment units, contaminated and non-contaminated. In the nearshore environment where contaminated sediments present critical environmental problems, one typically encounters a high degree of sediment variability over relatively small geographic areas. This creates the potential for inappropriate remediation efforts based upon the assumption of widespread sediment homogeneity. A reliable, cost-effective hydroacoustic reflection-profiling technique is available to map a given site accurately, from which an efficient physical sampling program can be developed.

Since most contaminants have an affinity to certain sediment types, detailed acoustic surveys, conducted as quantitative tests rather than for simply generating qualitative images, can provide accurate descriptions of bulk sediment properties. The characteristics of calibrated acoustic reflection data can be correlated to bulk sediment properties such as density, porosity, permeability, mean grain size, and sediment thickness through assessments of acoustic impedance, velocity, and absorption using proven Biot-based analytical techniques.

Habitat Restoration Goal-Setting and Actions—Bellingham Bay Demonstration Pilot Project

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Tom Schadt
Anchor Environmental, L.L.C.

Mike Stoner
Port of Bellingham

Rachel Friedman-Thomas and Lucille Pebles
Washington Department of Ecology

Abstract

The objectives of this paper are to describe the relationship of the habitat restoration element of the Bellingham Bay Demonstration Pilot Project to other key elements of the Pilot Project (i.e., disposal siting, sediment cleanup, source control, aquatic land uses); to describe the process used by the project's Habitat Subcommittee to develop a long-term vision for habitat restoration and mitigation in Bellingham Bay; to identify the range of habitat restoration and mitigation actions and

specifically where these actions could occur; and to identify the mechanism by which these actions were prioritized and integrated into disposal siting, sediment clean up and source control actions. GIS mapping and analysis tools help to illustrate historic and current-day conditions and habitats in Bellingham Bay and to determine priority areas for restoration. Multiple actions, including substrate modification, removal of remnant structures, changing elevations, removing shoreline fills, and restoring eelgrass and kelp are identified as actions that can be integrated and implemented with contaminated sediment disposal and other project elements to achieve the project's process, partnering, and environmental objectives. This paper will also illustrate the partnering required between state, federal, tribal, and local entities to develop a comprehensive vision for short- and long-term habitat restoration and mitigation in Bellingham Bay.

Development of a Bioaccumulation-Based Sediment Cleanup Level for Mercury in Bellingham Bay

Laura Weiss
Washington State Department of Ecology

Clay Patmont
Anchor Environmental

Abstract

Bioaccumulative chemicals in sediments can pose a human health risk via the consumption of contaminated seafood. At the Whatcom Waterway cleanup site in Bellingham Bay, empirical data were used to develop a sediment cleanup level for mercury that is protective of human health.

Historic mercury releases have resulted in a well-defined sediment mercury concentration gradient offshore from the Whatcom Waterway. A similar mercury concentration gradient was also observed in adult male Dungeness crab muscle tissue samples collected within the bay. Several data analysis methods were evaluated. A simple linear regression equation described the relationship between the measured tissue concentrations and the home-range average surface sediment mercury concentration. This empirical sediment-to-tissue regression relationship was also consistent with age-adjusted data for bottomfish.

Using risk assessment techniques, a tissue mercury concentration was calculated to protect tribal fishers who may consume relatively large amounts of seafood from Bellingham Bay. This target tissue concentration was then input into the empirical sediment-to-tissue regression relationship to determine a site-specific, health-based sediment cleanup level for mercury. At the Whatcom Waterway site, areas exceeding the health-based cleanup level generally fell within those areas of the site also targeted for cleanup to address ecological concerns.

5B: Sediment Evalutation and Cleanup

Questions & Answers

A: [In response to a question that was not recorded:] ... a couple of different reasons. One is to make sure that we've got our sources identified, and Rachel has been the one that's really been pushing us to make sure that we're taking a clear look at that.

Comment: Just for your general information, the 3O3(d) impairments in Bellingham Bay are separated by the toxic sediments that have been identified through the Bellingham Bay action program and are being rolled into our pilot project. In addition, there's the impact form the Nooksack, primarily fecals and temperature. We're not dealing with those issues. That's got a whole other body of folks addressing that issue. But from the contaminated sediment standpoint, we are looking very, very closely at the components that constitute a TMDL, whether it's a modeling exercise vs. a cleanup exercise, and we're working closely with many of the Ecology headquarters folks to literally take these first steps in trying to define what a TMDL means, and whether our pilot project then fits that definition. I think we're pretty close, but you know as well as I that it's pretty nebulous right now.

Q: My name is Tor Bjorkland from the School of Oceanography at the UW. My question is for either Tracy or Mike. $650,000 has appeared to result in a comprehensive well-thought-out plan of action for Bellingham Bay. I'm unclear, however, on how you've planned the transition between funded planning and unfunded cleanup once the planning stage ends in the fall of 98.

[Answer not recorded.]

PUGET SOUND RESEARCH '98

SESSION 5C

PLANKTON AND NUTRIENTS

Session Chair:

Jan Newton
Washington State Department of Ecology

Temporal and Spatial Distribution of Paralytic Shellfish Poisoning (PSP) in Puget Sound Embayments

Tim Determan
Office of Shellfish Programs, Washington State Department of Health

Introduction

The Washington State Department of Health is mandated to protect the health of consumers from shellfish contaminated with toxins, including biotoxins, such as paralytic shellfish poisoning (PSP) toxin. To meet the mandate, DOH monitors shellfish from hundreds of sites throughout the marine waters of Western Washington.

Paratytic shellfish poisoning occurs when people consume shellfish containing excessive levels of PSP toxin. Paralytic shellfish poisoning has also been noted in populations of birds and marine mammmals. Excessive levels of PSP toxin are produced by the dinoflagellate *Alexandrium catenella* during blooms that usually occur from spring through late autumn.

PSP toxin is one of a family of neurotoxins called saxitoxin. Saxitoxin disrupts nerve transmission. Symptoms can progress from numbness and tingling of lips, loss of muscular coordination, to respiratory arrest and death. Symptoms develop after 1–2 hours of eating contaminated shellfish. There is no known antidote. Death results in about 15% of cases worldwide (Nishitani et al., 1994). The U.S. Food and Drug Administration has set a standard for PSP at no more than 80 micrograms of PSP toxin in 100 grams of shellfish tissue.

PSP has a long history in northwest waters. In June 1793, four crewmen with Captain Vancouver's expedition became sick and one died shortly after eating shellfish along the coast (Strickland, 1983). Several PSP-related deaths occurred in 1942, which prompted the annual closure of the Strait of Juan de Fuca and the coast. By the 1970s, closures were occurring in the San Juans and Bellingham. In September 1978, heavy rains followed by warm "Indian Summer" weather produced a number of PSP illnesses from Saratoga Passage to as far south as Vashon Island (Strickland, 1983). In 1988, excessive PSP levels were detected in shellfish from Carr and Case inlets in south Puget Sound. In 1992, PSP went above the detection limit (38 micrograms per 100 grams shellfish tissue) in Hood Canal shellfish as far south as Seabeck.

In the late 1980s, the Puget Sound Water Quality Authority established the Puget Sound Ambient Monitoring Program (PSAMP). As a PSAMP agency, DOH designated a number of PSP sampling sites throughout Puget Sound and the Strait of Juan de Fuca to address PSAMP goals. This technical report addresses two questions based on PSAMP goals: 1) how levels of PSP toxin in shellfish change from place to place and over time; and 2) whether changes are related to human activities. The following analysis is an attempt to address these questions.

Methods

PSP sites are usually sampled twice a month by citizens, shellfish growers, or staff of counties, tribes, or DOH. The sampling frequency is increased in the event PSP in shellfish rises to unsafe levels. Blue mussels (*Mytilis edulis*) or several other *Mytilis* species are sampled "wild" from floats, pilings and rocks, or are taken from wire mesh cages (40 cm x 40 cm x 20 cm; 2.5 cm mesh size). These cages are suspended about one meter deep below floating docks. Seventy to 100 mid-sized mussels are taken to provide 100 grams of tissue for analysis. The mussels are put into one-gallon ziplock bags, packed into ice-bearing boxes, and shipped to the W.R. Geidt Public Health Laboratory in Seattle. The samples are analyzed with the mouse bioassay (APHA 1984).

PSP toxin in shellfish (where it occurs) is variable from year to year and within the same year. This variability is evident in Figure 1. Figure 2 shows an expanded view of 1992 (enclosed in the box in Figure 1).

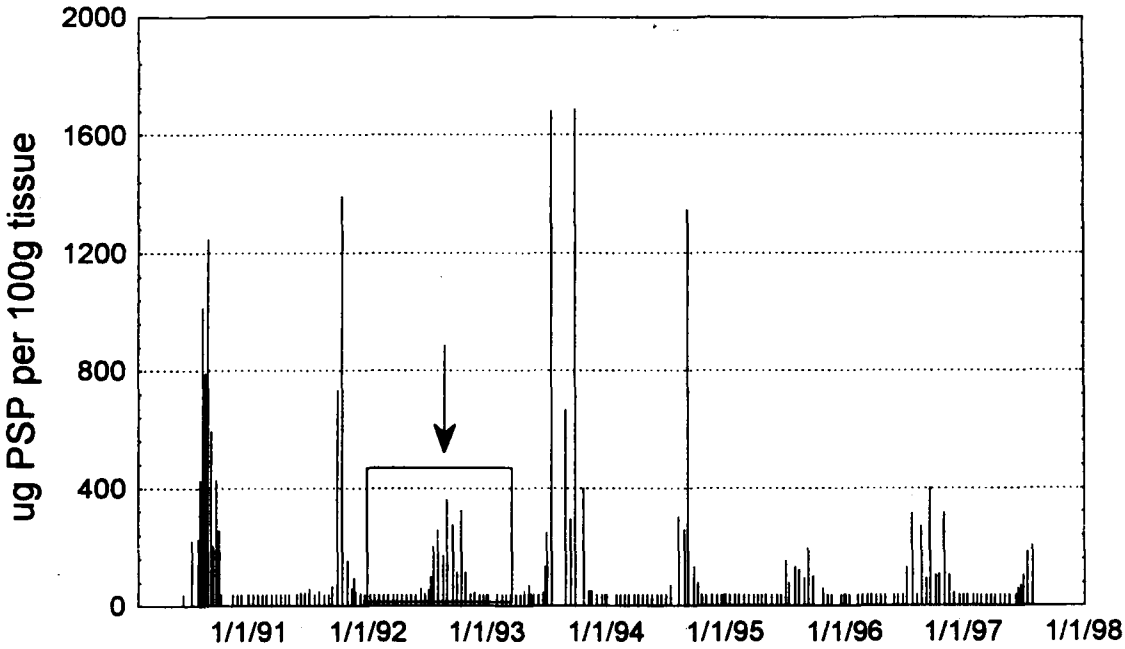


Figure 1. PSP at Sequim Bay (Battelle Labs).

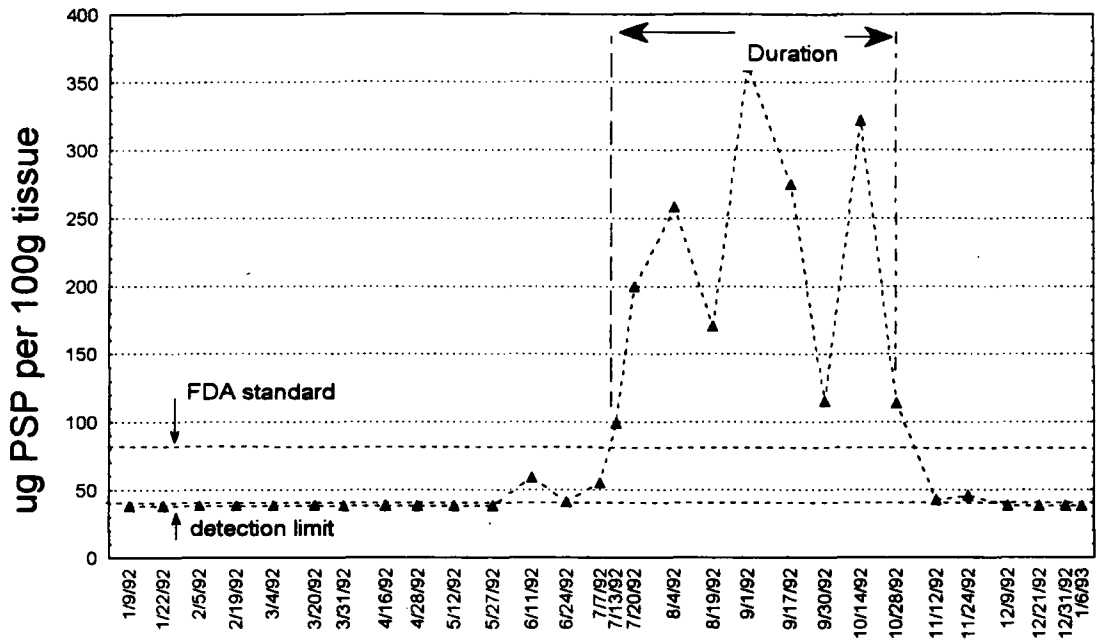


Figure 2. PSP at Sequim Bay (Battelle Labs) 1992.

Two criteria were developed to reduce the highly variable data into a single-value representation for each individual year: 1) "Duration" and, 2) a proposed value termed the "Relative Intensity Index" or RI Index. The concepts are displayed in Figure 2.

The "Duration" is the total number of days in a year when PSP toxin levels in shellfish exceed the FDA standard of 80 micrograms per 100 grams shellfish tissue (see Figure 2).

The RI index is the ratio of the total PSP production (the area under the dotted line connecting PSP levels in Figure 2) to a "standard minimum production" (the area under the dotted line marking the minimum detectable level of PSP, which is 38 micrograms per 100 grams shellfish tissue).

PSP duration provides a clear measure of public health impact (i.e., the period of time when shellfish are unsafe to eat). The PSP RI index considers not only the duration of a bloom, but changes in toxin levels during the bloom. The example in Figure 2 shows PSP duration of 107 days, or nearly a third of the year. The PSP RI index was estimated to be 2.6. Note that if a site shows no PSP during any particular year (i.e., PSP duration is zero), the RI index equals 1. In the future, the RI index may be used to test correlations with environmental factors (i.e., water stratification, nutrients, etc.). Both duration and RI indices were calculated for this technical report. However, the discussion will be restricted to PSP duration only.

Results

PSP criteria were calculated for 24 PSAMP sites. The period of record was 1991 through 1997 for most sites. However, some sites were not sampled until 1992 or 1993. Criteria were calculated only for those years when sampling was done throughout the year.

Figure 3 summarizes PSP impact at the PSAMP sites. PSP duration during the most recent three years (1995 through 1997) was combined into a single "total duration" value. High PSP impact was defined as having a total duration of 100 to 120 days. Moderate PSP impact means total duration of 30 to 60 days. Low PSP impact is total duration of 1 to 15 days. No PSP impact means there were no days when PSP in shellfish exceeded safe levels.

Three sites rated high PSP impact. Two are on the Strait of Juan de Fuca (Sequim Bay State Park and Discovery Bay near Maynard). A third was Quartermaster Harbor in the Main Basin of Puget Sound.

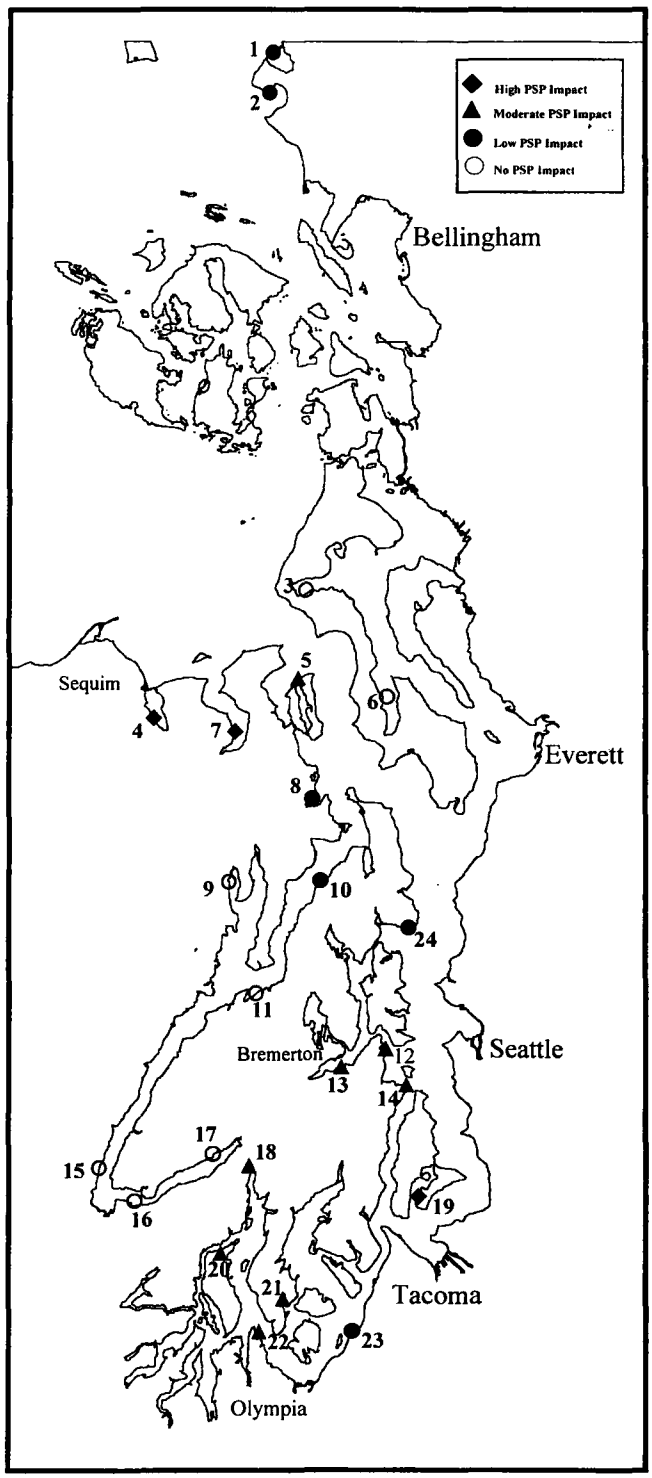
Eight sites showed moderate PSP impact. One is on the Strait (Kilisut Harbor). Three others (Port Orchard, Manchester, and Southworth) are in the Main Basin. The remaining four sites (North Bay, Jarrell Cove, Johnson Point on Nisqually Reach, and Filucy Bay) fell into the moderate group largely due to a very intense bloom in south Puget Sound in late fall 1997. These sites historically have experienced only occasional PSP blooms of low intensity and short duration.

Six stations ranked low in PSP impact. These sites include Port Ludlow and Lofall (in or near upper Hood Canal); Kingston (Main Basin); Steilacoom (south Puget Sound); Drayton Harbor and Birch Bay (both in Strait of Georgia).

The remaining seven sites showed no PSP impact. Five sites are in south Hood Canal, and two (Penn Cove and Holmes Harbor) are in Saratoga Passage.

Figure 4 shows results at four sites on the Strait of Juan de Fuca. PSP duration is consistently prolonged at Battelle Labs, Sequim Bay. In a year-by-year (1993–1996) comparison, PSP duration at Sequim Bay State Park (in the south end of the Bay) was lower than Battelle Labs (near the mouth of the Bay). (Criteria for 1997 were not calculated for Battelle Labs due to closure in July for safety and liability concerns.) This suggests a gradient of effect from the mouth to the head of Sequim Bay.

Discovery Bay (near Maynard) showed slightly less impact than Battelle Labs. Kilisut Harbor (Fort Flagler State Park) was the least affected. All four sites show peak duration in 1993. Sequim Bay State Park shows peak duration in 1993 and 1997. The other sites show peak duration in 1993 only.



1 Drayton Harbor
2 Birch Bay Village
3 Penn Cove
4 Sequim Bay
5 Fort Flagler
6 Holmes Harbor
7 Discovery Bay
8 Port Ludlow
9 Quilcene Bay
10 Lofall
11 Seabeck
12 Manchester
13 Port Orchard
14 Southworth
15 Hoodsport
16 Alderbrook Inn
17 Belfair/Allyn Ramp
18 North Bay
19 Quartermaster Harbor
20 Jarrel Cove
21 Filucy Bay
22 Johnson Point
23 Steilacoom
24 Kingston

Figure 3. Paralytic shellfish poisoning (PSP) toxin in Puget Sound mussels from January 1995 through December 1997.

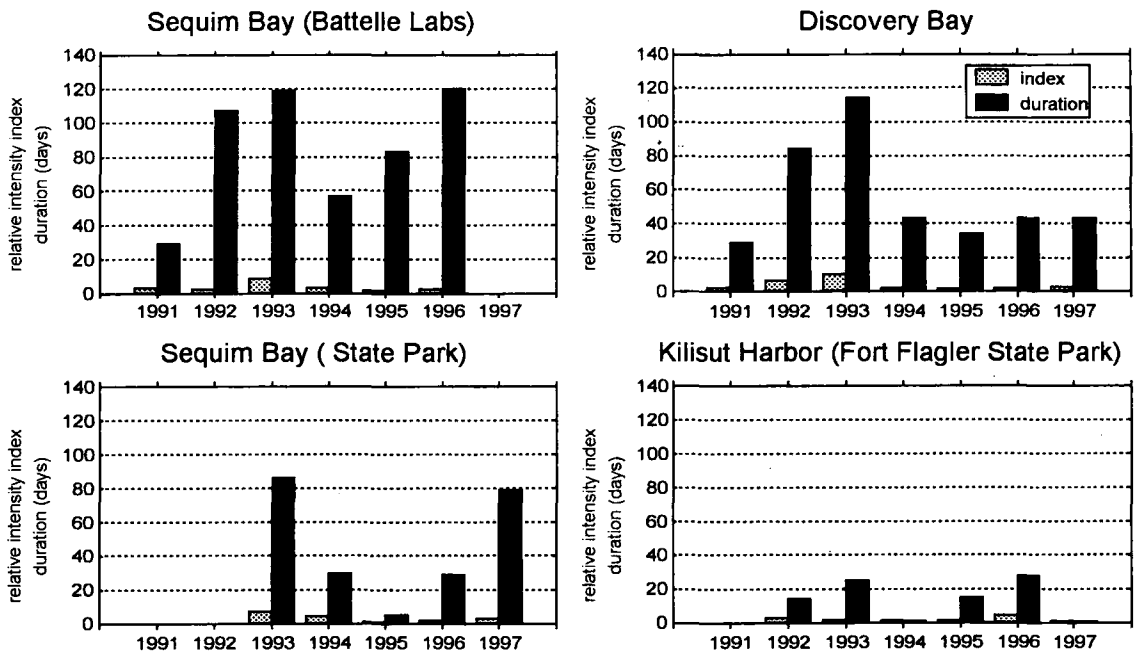


Figure 4. PSP in the Strait of Juan de Fuca.

Figure 5 shows results from three sites in the north end of Puget Sound's Main Basin (including Port Orchard in Sinclair Inlet). Figure 6 shows two sites in the south end of the Main Basin. Durations in Quartermaster Harbor (Dockton County Park, Maury Island) were similar to those of Sequim and Discovery Bay sites. On the other hand, the other Main Basin sites tended to have much less duration. (Note the different scale showing criteria for Quartermaster Harbor graph compared to other Main Basin sites).

Kingston, Manchester, and Southworth showed peak PSP duration in 1993 and 1997. Other years showed no PSP at all (i.e., duration = 0; RI Index = 1). PSP duration in Port Orchard was comparable to most Main Basin sites. However, Port Orchard site differed in timing of peak durations (1995 and 1997). PSP duration in Sinclair Inlet doesn't seem to be overly stimulated by nutrient input from adjacent urban sources (e.g., sewage treatment plants, combined sewer overflows, and stormwater runoff).

Figure 7 shows PSP duration at four sites in south Puget Sound. Peaks occurred in 1994 and 1997. Significant PSP was undetected in other years. In peak years, blooms occurred later than elsewhere in Puget Sound. In fact, the 1997 bloom began in late October and continued through January 1998 (F. Cox 1998, this volume).

Impressions

Spatial Patterns

Maximum PSP duration occurred at Sequim and Discovery Bays on the Strait of Juan de Fuca and at Quartermaster Harbor in the Main Basin of Puget Sound. Saratoga Passage and Hood Canal were free of PSP.

Although Saratoga Passage has had no PSP in recent years, intensive blooms occurred there in the late 1970s. Based on this experience, there is no reason to conclude that the intensive blooms in south Puget Sound this year will become a permanent event. However, lack of complete understanding of phytoplankton dynamics makes reliable predictions impossible. There appears to be no evident relationship between PSP duration and human activity.

Temporal Patterns

A number of sites in the Strait of Juan de Fuca and the Main Basin of Puget Sound show peak PSP duration in 1993 and 1997. South Puget sites show peak duration in 1994 and 1997. This pattern suggests PSP bloom activity in Puget Sound may be cyclic. Continued PSP monitoring coupled with study of interaction with other environmental data is needed to confirm this hypothesis.

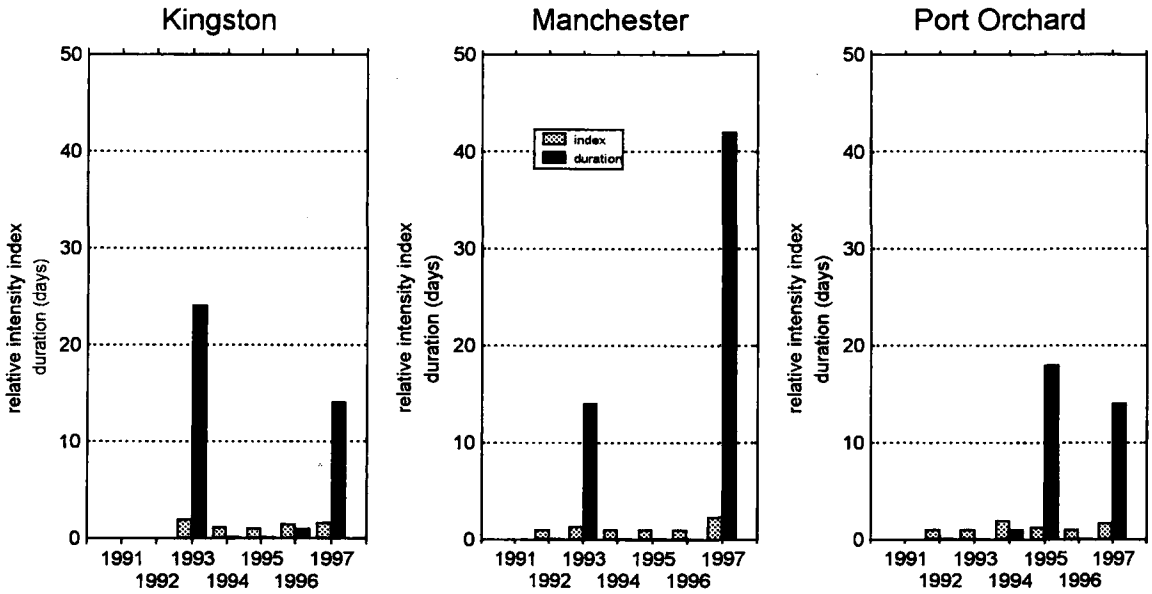


Figure 5. PSP in Main Basin (north).

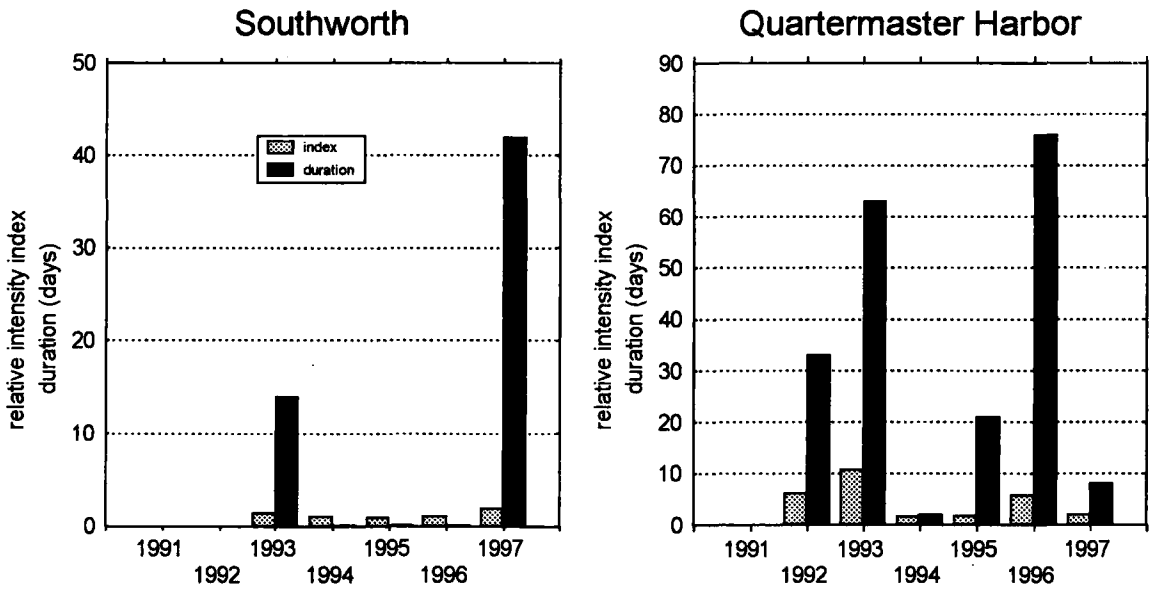


Figure 6. PSP in Main Basin (south).

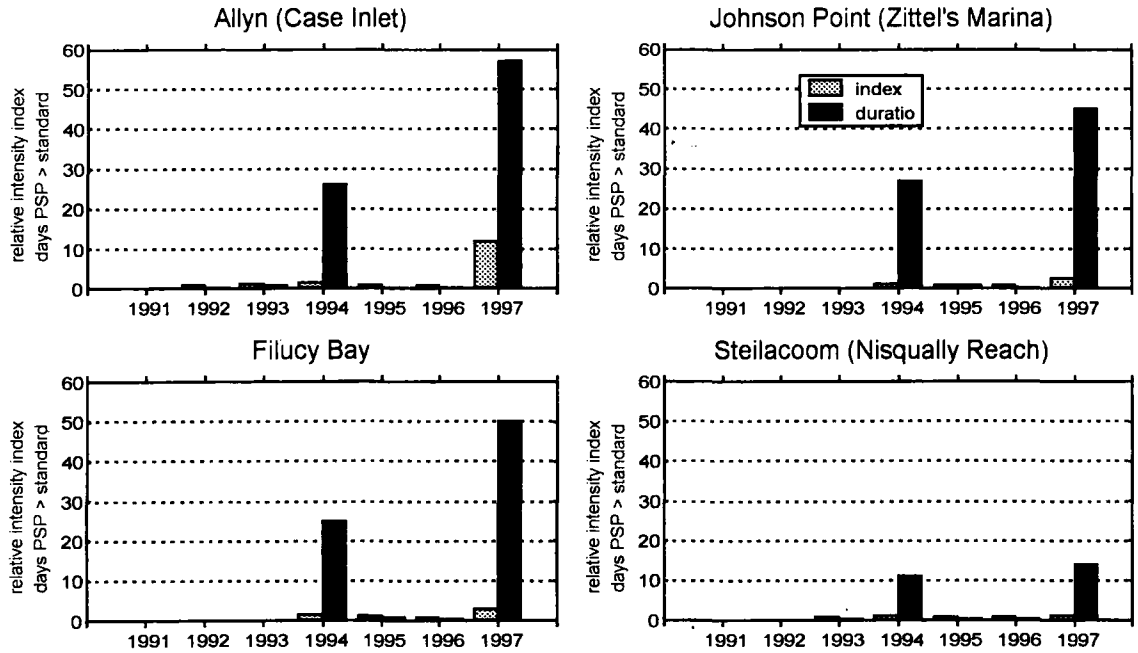


Figure 7. PSP in south Puget Sound.

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Zooplankton Composition and Abundance in Budd Inlet, Washington

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Introduction

Situated in southern Puget Sound, Budd Inlet is a narrow water body (roughly 2.5 x 11.5 km) with a north-south orientation (Figure 1). The inlet is well mixed in the winter and becomes stratified during the summer (WDOE 1997). The inlet is shallow, mostly less than 10 m deep. Tides are semi-diurnal with a range of 14.4 ft. The southern end of the inlet receives the majority of the fresh water entering the inlet and is home to most of the commercial activities in the inlet.

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 has been proposed as a partial solution to this difficulty. A 13-month intensive field effort was made to determine the feasibility of this option. One tool that was created to help assist in this decision was a model that incorporated both water quality and circulation information. Because zooplankton make demands on and affect water quality, zooplankton sampling and analysis were included in the field portion of the Budd Inlet modeling study.

The circulation study, which was a major component of the overall investigation of Budd Inlet can be summarized, as follows (see Ebbesmeyer and Coomes 1998 for a comprehensive description of the circulation model): marine water enters the inlet along the western shore as a relatively dense, cold bottom layer. Fresh water leaves the inlet along the eastern shore as a lighter, warmer layer. These layers are well mixed during the winter months and become stratified in the summer. The central portion of the inlet contains a counterclockwise gyre that recirculates approximately 16% of the outgoing water back into incoming water. Flushing times for the inlet are short; the inner inlet flushes within one day, while the whole inlet does so within 10 days.

These processes in Budd Inlet may in part determine the structure of its zooplankton assemblages there. In order for zooplankton species to maintain viable populations in dynamic systems, reproductive rates must be equal to the export of individuals through death or transport (Ketchum 1954; Gupta et al. 1994) or they must have some other method by which to maintain critical densities (e.g., vertical migration to make use of stratified flows: Trinast 1975; Cronin and Forward 1979; Woolridge and Erasmus 1980; Cronin 1982; Hough and Naylor 1991, 1992; Morgan et al. 1997). Therefore, one question posed in this study is whether hydrographic phenomena in Budd Inlet (e.g., circulation patterns) are coincident with identifiable zooplankton assemblages or abundance patterns.

Because zooplankton investigations in Puget Sound and other Pacific Northwest estuaries are very rare, this study will also provide a basis for comparison to other coastal and estuarine data from the northeastern Pacific. It will also serve as a baseline of data for comparison with future zooplankton sampling in Puget Sound.

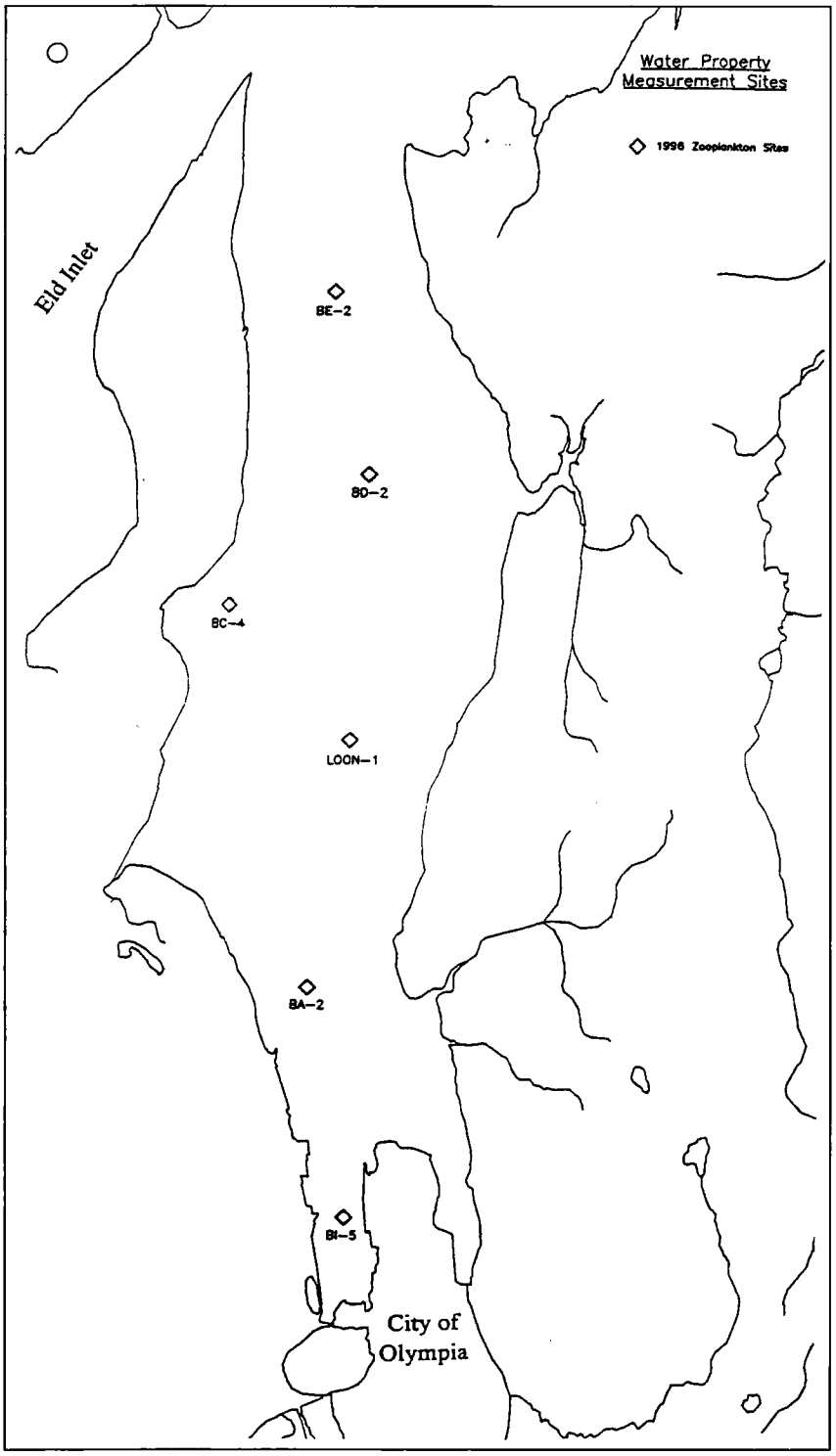

Figure 1. Budd Inlet, Puget Sound, Washington.

Methods

Zooplankton samples were taken approximately bimonthly for a total of 21 times within 12 months at six stations. The stations were arrayed roughly in a line starting in West Bay and continuing up the center of the inlet (Figure 1). The stations sampled were designated as follows: BI-5, BA-2, Loon-1, BC-4, BD-2, and BE-2. Samples were collected using a 0.5-m 220-µm mesh net, which was towed vertically through the water column by hand. Samples were fixed on board and had a final formaldehyde concentration of approximately 10% by volume. A Hensen's Stempelpipette was used for quantitative subsampling of the zooplankton fraction between 0.253 and 2 mm. Zooplankton larger than 2 mm were counted in their entirety, except on rare occasions (very numerous or split for biomass measurements before identification), in which case they were split with a Folsom plankton splitter. After taxonomic identification, each sample was dried for 24 hr at 60 _C and weighed to the nearest 0.001 g.

For other components of this study, the inlet was divided into three regions: inner, central, and outer. The inner inlet was defined as an area south of an east-west line drawn from Priest Point (Figure 1). Station BI-5 is located within this region and station BA-2 is located on its boundary. The central inlet encompasses the area from the BA transect to the BC transect; station Loon-1 is in this portion and station BC-4 lies on the boundary. The outer inlet contains station BD-2 and BE-2 and is defined as the area north of the BC transect to the inlet mouth.

Results

Stations within and on the boundaries of the central inlet (BA-2, Loon 1, BC-4) usually had the highest abundance levels (Figure 2). Loon-1, in the center of this area, consistently had the highest abundances, and had the largest peak of over 6.7×10^4 m^{-3} individuals in June (Figure 2). In relation to the central inlet stations, average abundance levels decreased toward both the inner inlet (5.3×10^2 individuals m^{-3} at BI-5) and outer inlet (3.7×10^2 individuals m^{-3} at BE-2) (Table 1). Average biomass levels were highest at station BA-2 (Table 1), but the highest single biomass measurement occurred at station BI-5 on 1 July (Figure 2). Peaks in taxa that were large in size, but low in relative abundance sometimes caused dissimilarity in abundance and biomass data. For example, the discrepancy between biomass and numbers at BI-5 on 1 July 1997 (Figure 2) was caused by an increase in cnidarians (Figure 3).

Table 1. Average total zooplankton abundance and biomass (dry weight) for stations sampled over a 12-month period in Budd Inlet, Washington.

Station	Location in Budd Inlet	Abundance (Individuals m^{-3})	Biomass (grams)
BE-2	**Outer**	3656	0.079
BD-2	Outer	5786	0.109
BC-4	Central	7527	0.081
Loon-1	Central	11898	0.105
BA-2	Central/Inner Border	9831	0.144
BI-5	Inner	5325	0.120

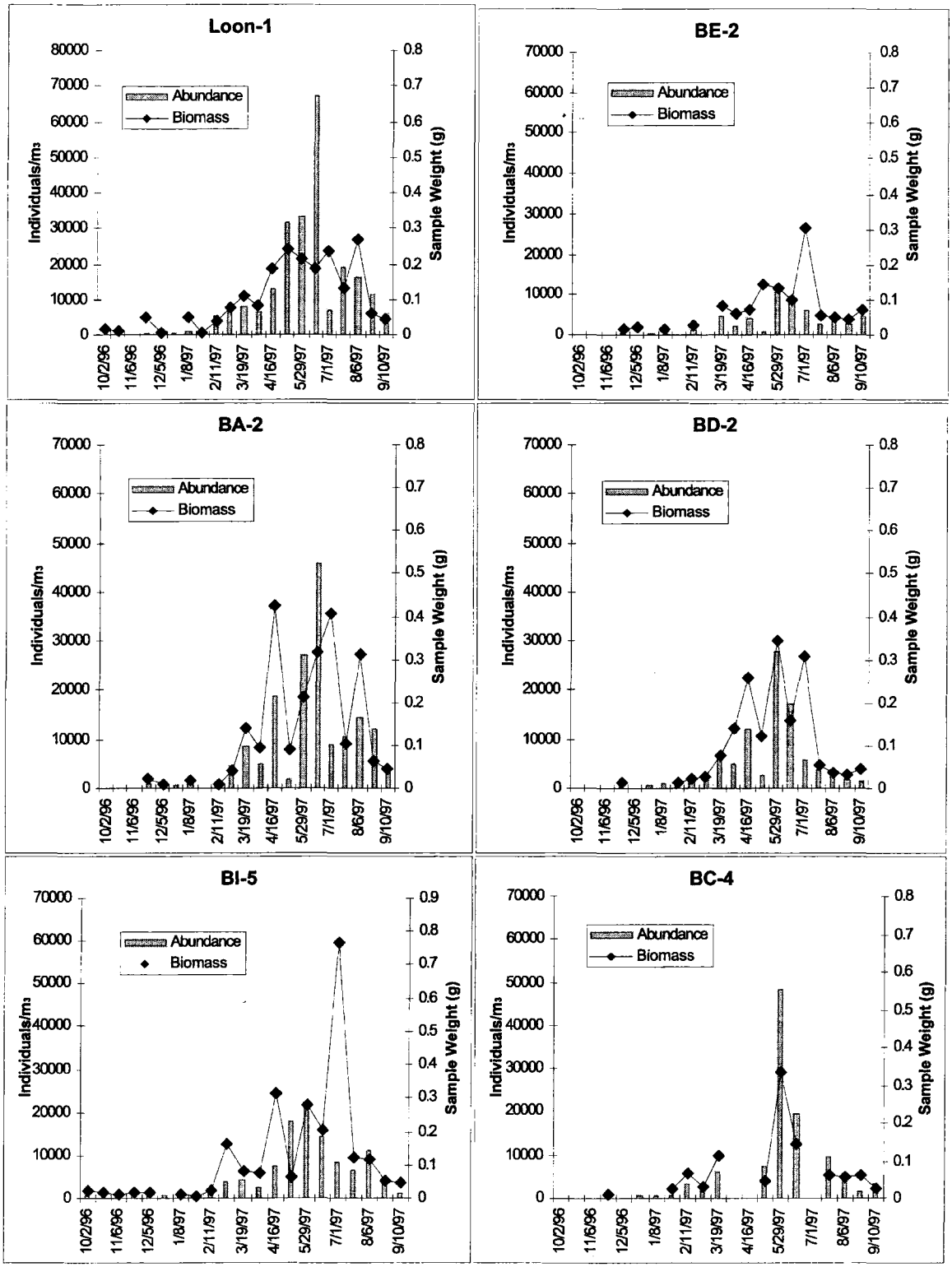

Figure 2. Zooplankton abundance and biomass in Budd Inlet, October 1996 through September 1997.

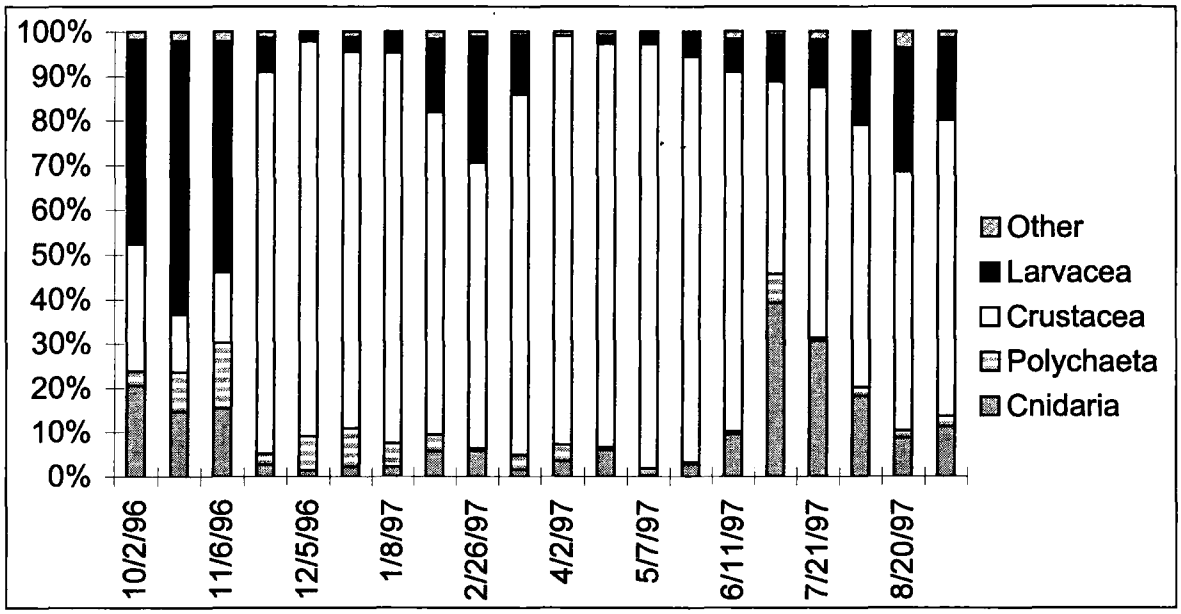

Figure 3. Zooplankton in inner Budd Inlet (station BI-5), October 1996 through September 1997.

Temporal variation played a larger role than spatial variation in determining zooplankton composition. At a relatively high level of taxonomic classification, crustaceans usually dominated zooplankton composition throughout the year (see Figure 3 for an example from one site). Other prominent groups included larvaceans, cnidarians, and polychaete annelid larvae (Figure 3). Larvaceans exhibited a distinct seasonality with large abundance peaks in Autumn 1996, when they were the numerically dominant group; smaller peaks occurred in February and August 1997 (Figure 3). In contrast, on a within-inlet basis, the general taxonomic composition of the zooplankton was usually similar on any given date (see Figure 4 for an example from one date).

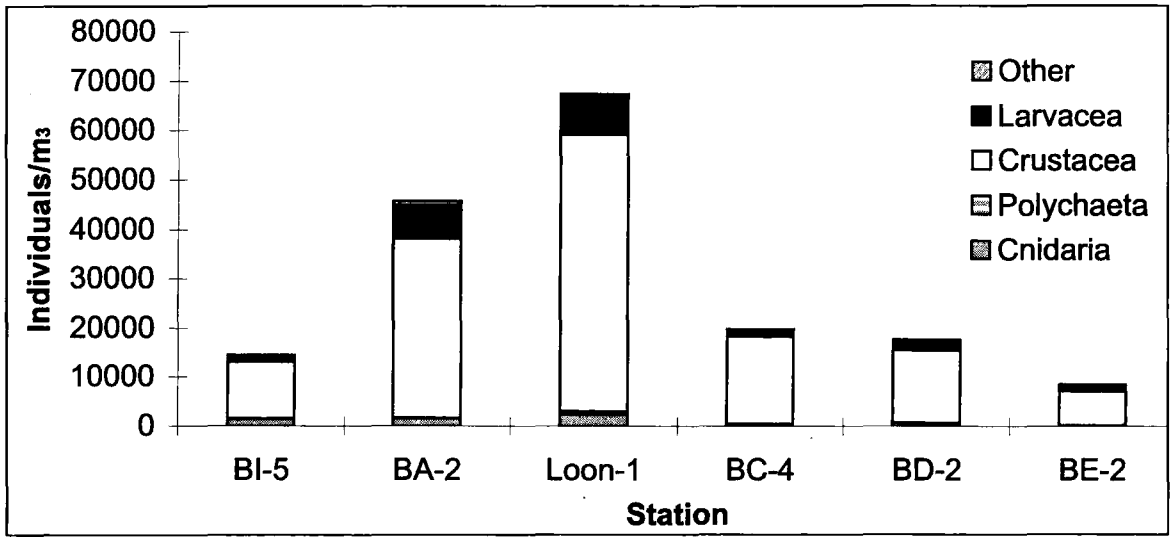

Figure 4. Zooplankton composition in Budd Inlet, 11 June 1997.

Of the crustaceans, calanoid copepods were usually numerically dominant (see Figure 5 for an example from one site). However, some taxa were seasonally abundant and exceeded or were similar to the numerical proportion represented by calanoids. These included planktonic larvae of barnacles and brachyuran and caridean decapod larvae in the spring and marine cladocerans (*Podon leuckarti* and *Evadne nordmann*) in the autumn (Figure 5). Of the calanoid copepods, the genus *Acartia* (subgenus *Acartiura*) was the most abundant in spring-early summer in all three regions of the inlet (see Figure 6 for examples from central, inner, and outer inlets). In late summer-early autumn, the numerically dominant calanoid was *Paracalanus* spp. In winter samples, numerical composition was more site-specific, with *Acartia* dominant in the inner inlet, *Paracalanus* spp. in the outer inlet (except in January, when *Pseudocalanus* spp. dominated), and a relatively even distribution of taxa in the central inlet (Figure 6).

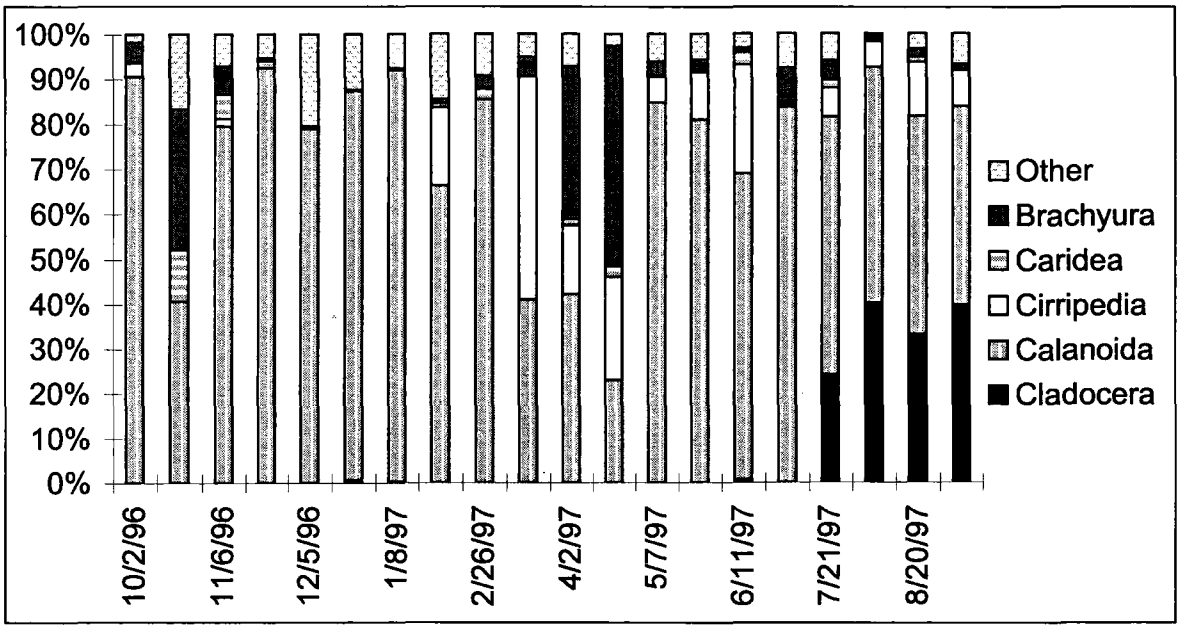

Figure 5. Crustacean composition in inner Budd Inlet (station BI-5), October 1996 through September 1997.

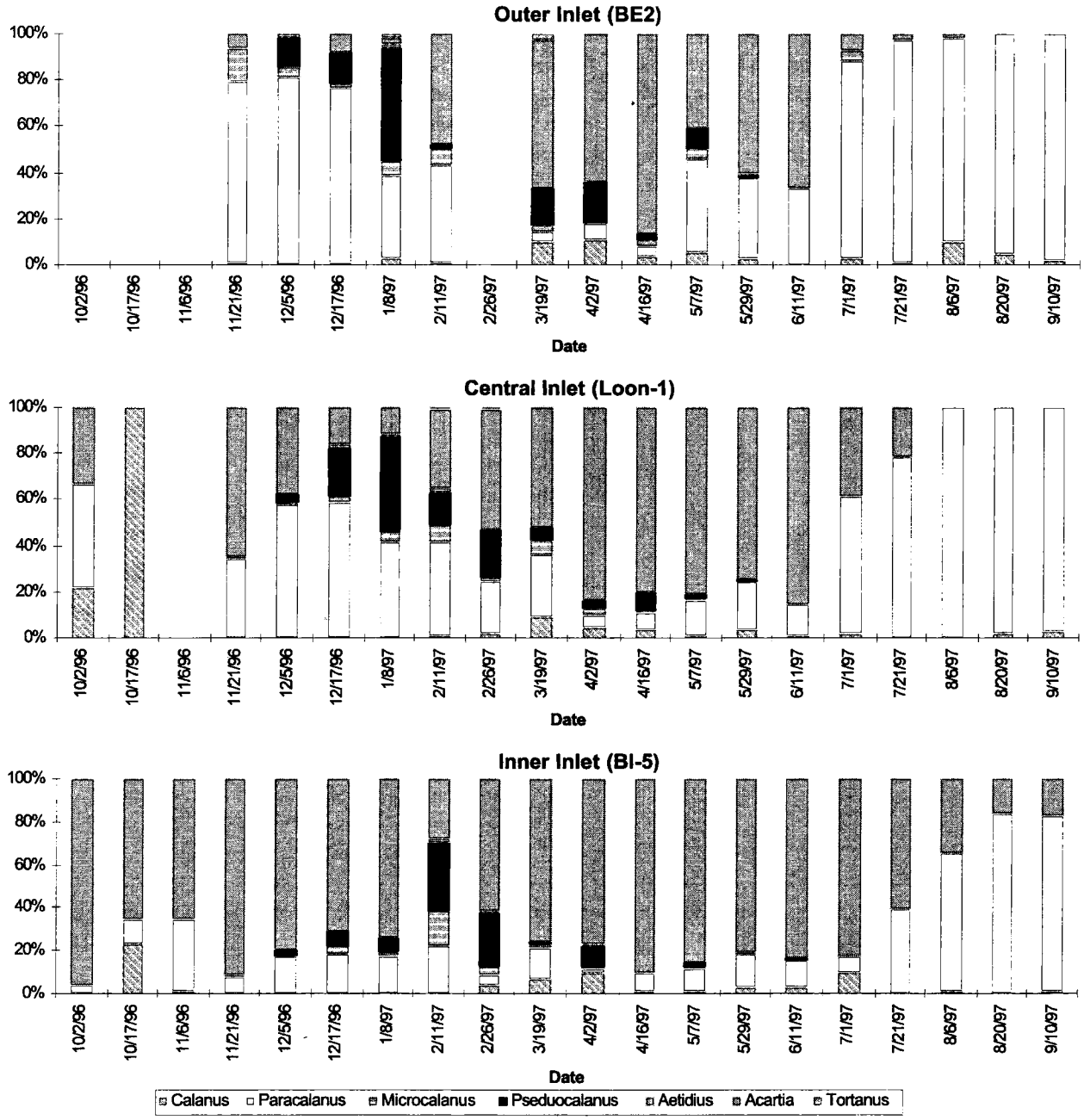

Figure 6. Calanoid copepod assemblages in Budd Inlet, October 1996 through September 1997.

Discussion

Prior to this study, we had hypothesized that the largest zooplankton abundance might occur in the inner inlet, based on previous studies showing high nutrient input into this region (WDOE 1997). However, our finding of highest zooplankton abundances in the central inlet agrees with the measured circulation patterns that showed relatively short (~1 day) flushing time in the inner inlet and a gyre in the central inlet (Ebbesmeyer and Coomes 1998). The combination of the zooplankton data and the circulation model suggests that the gyre increases retention of zooplankton in the central inlet.

Our finding that temporal variation was larger than within inlet variation is consistent with other studies of zooplankton in nearshore and estuarine systems (Minello and Matthews 1981; Sameoto 1975). These temporal and spatial variations have implications for growth and recruitment of important nearshore planktivorous fish such as Pacific herring, smelts, and juvenile salmon. For example, both *Paracalanus* and *Acartia* spp. have been found to be major prey items in the diets of these fish in both Puget Sound and coastal estuaries (J. Cordell, unpublished data; K. Fresh, Washington Department of Fish and Wildlife, unpublished data). In addition, planktonic prey (calanoid copepods, euphausiids, decapod larvae, and larvaceans) often dominated the diets of several species of Pacific salmon and their fish prey (Pacific herring, Pacific sand lance, and surf smelt) collected throughout Puget Sound (Fresh 1981; Fresh et al. 1979; Simenstad 1979). Therefore, both seasonal and longer-term (e.g., decadal) trends in Puget Sound zooplankton abundance may have implications for management of planktivorous fish and their predators (e.g., adult Pacific salmon). However, previous quantitative zooplankton studies of Puget Sound are rare, consisting of several unpublished student theses (Dempster 1938; Hebard 1956; Dumbauld 1985), and there are no past or current longer-term zooplankton monitoring programs in nearshore marine waters of the Pacific Northwest.

The zooplankton assemblages that we found in Budd Inlet had many taxa in common with those found elsewhere in Puget Sound and Hood Canal but had generally lower relative abundances of those species that dominated the deeper main basins of Puget Sound, Hood Canal, and the Strait of Juan de Fuca (Damkaer 1964; Chester et al. 1980; Dumbauld 1985; Bollens et al. in prep). In the dominance of shallow-water taxa such as *Acartia* (*Acartiura*) spp., *Paracalanus* sp., *Podon*, and *Evadne*, our data are similar to those from shallow basins of Puget Sound, San Francisco Bay, and numerous other shallow embayments on the Pacific coast (B. Frost, UW School of Oceanography, unpublished data; J. Cordell and S. Bollens, unpublished data; Trinast 1975; Miller 1983; Ambler et al 1985; Kimmerer et al. 1993). One difference between our results and these studies was the dominance of *Acartia* (*Acartiura*).

With the increasing effects on water quality due to rapid urbanization of the Puget Sound region (e.g., domestic sewage, nonpoint-source pollution), temporal changes in zooplankton abundance and assemblage structure might be expected, with following consequences for higher trophic levels. Given the potential importance of zooplankton as indicators of water quality and ecosystem function, we strongly recommend that future environmental monitoring of Puget Sound include a basic zooplankton component.

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Nitrogen Budget for the Strait of Georgia

Paul J. Harrison
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Abstract

The nitrogen budget for the Strait of Georgia has been estimated, and this budget is used to assess the potential for eutrophication of this system by anthropogenic nutrient inputs. The exchange of water by estuarine and tidal currents is rapid, and water in the Strait is estimated to turnover about once per year. Waters entering the strait carry naturally high nitrogen concentrations, and therefore natural nitrogen inputs from estuarine circulation are about one order of magnitude higher than inputs from sewage, rivers, groundwater discharge, and atmospheric contributions. The largest loss term for nutrients is the estuarine exchange, which may be influenced by variations in the Fraser River discharge and offshore oceanographic conditions (affects nitrogen concentrations of the incoming deep water). Sensitivity to anthropogenic nutrient addition varies with location. The most sensitive regions are inlets and fjords that have low flushing rates and adjacent urban centers.

Assessing Sensitivity to Eutrophication Using PSAMP Long-Term Monitoring Data from the Puget Sound Region

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Washington State Department of Ecology

Abstract

Puget Sound is an extremely complex and diverse environment, since it is a composite of bays, inlets, deep basins, and channels. Certain localized areas within Puget Sound are susceptible to eutrophication while others are not. This difference is largely driven by physical processes such as mixing and advection. At the same time of the year, Puget Sound phytoplankton growth is light-limited in some areas and nutrient-limited in others. Understanding the mechanisms driving primary production is key to assessing impacts of anthropogenic alterations, such as nutrient inputs. The degree of persistence of the density stratification is found to be a good indicator of sensitivity to eutrophication and low dissolved oxygen in the bottom waters. As part of the Puget Sound Ambient Monitoring Program, the Marine Waters Monitoring group at the Washington State Department of Ecology collects monthly monitoring data from various locations in the greater Puget Sound region. It has been possible to characterize sub-regions and localized areas in terms of their physical stability and biological productivity. Monitoring data in combination with targeted experiments have proven useful for assessing eutrophication sensitivity in the various regions of Puget Sound.

Effects of Elevated Nutrients from Fish Farm Wastes on Phytoplankton Productivity

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Edward A. Black
Ministry of Agriculture, Fisheries, and Food

Abstract

The potential impact of wastes from salmon aquaculture operations on biological production has been evaluated by four approaches: nutrient uptake rates and their role in utilization of nitrogenous farm wastes; the relative contribution fish farms make to available nitrogenous stocks and fluxes; the maximum phytoplankton biomass that could be released from fish farm wastes; and ecologically resolved phytoplankton production from nitrogen. Estimates calculated by each approach indicate the impact of these wastes is small in comparison to natural and other anthropogenic sources of nitrogen input. This results suggests that the industry in British Columbia is unlikely to have a significant impact at current production levels, although there is potential for local effects in areas of poor circulation or where net pens interfere with local current patterns. Further evaluation should consider whether increased nutrient concentrations would be sufficient to stimulate harmful blooms or whether, through changing nutrient ratios, there could be shifts such as from a diatom- to a flagellate-dominated community structure. There may be value in establishing scientifically based standards to which predicted impacts could be related, prior to development. Such evaluations require quantification of the amounts of wastes generated, the use of numerical models to predict impact, and the establishment of specific ecological standards or targets.

Interdecadal Variations in Developmental Timing of the Copepod *Neocalanus plumchrus* (Marukawa) in the Strait of Georgia

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University of British Columbia

D. L. Mackas
Department of Fisheries and Oceans Canada

Abstract

In coastal waters of the North Pacific, copepods of the genus *Neocalanus* dominate the spring and early summer mesozooplankton community. All *Neocalanus* species undergo a very strong seasonal vertical migration that is closely linked to their developmental cycle. In the Strait of Georgia (49_–50_N, 123_–125_W), the 30–50 day annual peak of mesozooplankton biomass has historically coincided with maximum surface layer abundance of maturing large *Neocalanus plumchrus* copepodites (C4 and pre-migrant C5). We present evidence for significant changes in the timing of the vertical migration component of the *N. plumchrus* life cycle during the past 25–30 years. In the Strait of Georgia, the developmental cycle is now about 25–30 days earlier than it was 30 years ago, with peak biomass now occurring in mid-April (compared to mid-May previously). The variability in timing, which appears to be coincident with warming trends in both surface and over-wintering deep water, is likely to be ecologically significant because it shifts relatively narrow seasonal windows of maximum grazing pressure on 10–50 mm prey, and it influences the availability of large copepodites to upper ocean predators such as salmon, herring, and hake.

5C: Plankton and Nutrients

Questions & Answers

Q: Tim Determan's plot of the paralytic shellfish poisoning was most interesting to me. I just remember looking at our PSAMP data for the Hood Canal, Holmes Harbor, and Penn Cove that those tend to be areas that have low DO in the late summer, and as a non-biologist, I kind of wonder if maybe there are any other vital plankton that are out competing Alexandria and I just wondered if there were any other hypotheses. Maybe a real biologist could tell me some other things. It seems that those areas are the same ones that have the lowest DO.

A: Well, I'm not a real biologist. I'm more of the nuts and bolts oceanographic type. Any biologist here could field that question. We don't have any implications at this point.

A: I think it's too soon to say. What regulates species succession is a classic question that we really struggle, as oceanographers, to try to answer because the environment is so complex. But as get better methods of detecting these things, some of the things that Vera is going to be speaking on, and some of the research. I'm going to put a plug in for Dr. Ginger Armbrust at University of Washington School of Oceanography. She's been using some molecular techniques to look at why one species develops vs. another. Combining that with the environmental idea I think we might get some answers. And I see Tim has thought of something.

Determan: I think people should keep in mind that we're looking at PSP toxins in shellfish and so whether you can take this data and translate it into what's going on in the water column is a matter of some question because we have to deal with the physiology of the shellfish as well the conditions in the water. This is a point I'd like to make particularly for the south Sound blooms that occurred this year. It's entirely possible that that late season bloom occurred and the shellfish took the stuff in. If the temperature dropped (and we have to take a look a the temperature data here), it could be that the pumping, filtration rate of the shellfish dropped and they essentially just held on to what they had for a longer period of time. So we've got to be kind of careful in making these shifts in thinking about PSP in shellfish tissue to what's going on in the overlying water column.

Forbes: I just want to reiterate that Beth spent three years working with me in the southern Gulf Islands looking at toxins or harmful algae in the water column and a number of oceanographic factors, and one the things that we were trying to do was to relate that to the Canadian paralytic shellfish poisoning monitoring program. In fact, we found very little correlation between high levels of *Alexandrium* that we found in the water column compared to nearby PSP monitoring sites. I think that PSP is very much localized in some environments and you cannot make a very clear link between harmful phytoplankton in the water column and toxicity in the nearby shellfish beds. But it's very difficult to make that link.

Q: Beth, I think the work you've done is really interesting and it may be highly significant when you compare, and I realize the data sets may not be there, those kinds of shifts in timing like that they're very reminiscent of some of these other interdecadal kinds of shifts we've seen, obviously, in the larger atmospheric conditions, but when you look at things like oyster condition, how fat the oyster is in its shell, salmon returns and all that, have you considered looking at some of those other factors and correlating them?

Bornhold: Yes, we're going to try and collect some of those data sets next. We just saw this change and have kind of gone with that for now. And that's what I say, look at the other shifts and try and compare and see if we're seeing other shifts.

Q: Paul, I know the paradigm right now is that nitrogen is one of the macronutrients that is controlling phytoplankton in Puget Sound, but have you given any thought to some micronutrients maybe being supplied by urban run off, sewage treatment plant, either some other some element, some vitamin or organic component?

Harrison: Did you have a particular one in mind?

Q: I've often said iron.

Harrison: Yes, iron is important now offshore, well offshore in the north Pacific, but not in the coastal regions. We get enough input, so that's not a problem. The next one likely to be limiting is phosphorus. If you do any bioassays, if you just look at any data, usually when the inorganic nitrogen is low and that's usually for a very brief time, a few days, often phosphate is sort of closer or close behind. One thing that is important and is quite interesting is coming out of the Fraser River when you measure nutrients in the plume, if you filter the samples which are really quite muddy, and then run the phosphate concentrations you find very, very low phosphorus concentrations. But if you don't filter them, and go ahead and do the analysis, you actually get quite high phosphorus concentrations. So there is a lot of phosphate absorbed to the sediments. We've done some preliminary bioassay work to show that quite a large portion of that phosphate absorbed to the sediments is actually biologically available on a slow basis. So I guess to answer your questions, number one would be nitrogen, number two would be phosphorus.

Amazingly enough, as I think Curt had suggested, silicate is quite high in the rivers. We have 60 micromolar coming out of the Fraser River. But periodically this can be drawn down to very low levels by the diatoms, which is quite amazing. So, of course, not all species need silicate, so you can go on and get dinoflagellates, so I think there's really nothing there in the micronutrient story.

And vitamins—I had a student do something with vitamin B-12, but I would be surprised if there's anything there. So it's mainly nitrogen dominated but only very brief periods of nitrogen limitation, quite amazingly enough. And even in the main part of Puget Sound I think because of wind mixing, they don't have the prolonged nitrogen limitation that you might find in other areas.

Comment: Well, I have to follow up with that and offer something I saw at ocean sciences, and if I hadn't seen the data myself, I would be pretty skeptical. Al Hansen had data from East Sound, and he's looking at iron concentrations and found that at a period in late July, or something like that, they had strong stratification and they actually found that iron was depleted in some of the zones due to this stratification. I also had to do with the oxygen content and what oxidation level the iron was in, whether it was bioavailable. He was making the case that you actually could find iron limitation in a place like East Sound, which was absolutely mind boggling to me. But I think it's some interesting research that we may be hearing more about.

PUGET SOUND RESEARCH '98

SESSION 6A

WATERSHEDS AND WATER QUALITY

Session Chair:

Joanna Richey
King County Department of Natural Resources

An Examination of Runoff Water Quality and Nutrient Export from a Forested Watershed Fertilized with Biosolids

Mark Grey and Chuck Henry
College of Forest Resources, University of Washington

Introduction

Applying biosolids to both low and high quality sites in the Pacific Northwest increases the growth and size of Douglas fir (Henry et al., 1994). Thousands of acres of timber lands are currently excluded from biosolids fertilization due to existing guidelines that suggest applications be limited to terrain with slopes less than 30% (WDOE, 1996). Generally, slopes exceeding 30% are found on forested sites, and this is certainly the case within a region known as the Mountains to Sound Greenway (MTSG) between Seattle and Snoqualmie Pass.

Part of the MTSG program involves using biosolids for forest fertilization and biosolids compost for disturbed land reclamation and restoration, i.e., stabilization of steep slopes and abandonment of logging roads. Biosolids is used as an organic fertilizer, as it contains high concentrations of nitrogen (N) (6–7%) and phosphorus (P) (2–3%) on a dry weight basis. A concern within the MTSG is water quality protection and enhancement. One of the largest surface water receiving bodies is Lake Sammamish and it is P-limited. Dissolved and labile P entering the lake are both available for uptake, and high total lake P concentrations cause toxic algae blooms.

Experimental Basis and Objectives

Few studies consider whole-watershed water quality responses to biosolids fertilization, and no studies consider the application of dewatered biosolids. Metro (1986) examined water quality in ephemeral streams draining treated and control watersheds at the University of Washington's Pack Forest following application of liquid biosolids at a rate of 45 Mg ha^{-1}. Researchers used a 15-meter buffer from ephemeral streams draining the watersheds and found no significant difference in organic or mineral forms of N and P between the two watersheds. Kimmins et al. (1991) applied liquid digested biosolids to a 3.58 ha area within the East Creek Watershed in British Columbia and used an extensive network of stream monitoring to assess water quality. Concentrations of total-N, NO_3^--N, NH_3-N, and total and PO_4-P in East Creek and ephemeral drainages were almost equal to or below pre-biosolids application levels. Stream data included the evaluation of a 100-year storm that occurred within one month following biosolids application.

One of the unknowns regarding the use of biosolids within steep, forested watersheds is when stream water quality is most vulnerable to fertilization effects. Intuitively, the critical time to assess whether or not biosolids will move from a particular site is during periods of prolonged rainfall. The duration of Pacific Northwest storms is longest in the late autumn and winter months, with intensity highly variable; rain-on-snow events can and do produce substantial runoff hydrographs in streams. The experimental design discussed here is based on quantifying the concentrations and export of nutrients from a headwater watershed under runoff event flow conditions. The assumption is that if mobile constituents in biosolids are to move from a site, it would occur soon after application (as decomposition is still low) and it would occur under heavy rainfall conditions during the winter when soil moisture content is high.

Alternatively, following a winter application biosolids decomposes and releases nutrients through mineralization. Depending on the extent of uptake and soil immobilization, this process generally elevates the concentration of nutrients in the soil solution. This could create a situation in

the autumn and early winter where available P or N production has exceeded uptake and the remaining P or N not taken up or immobilized by microbes could be lost to stream water during runoff events. A pattern of seasonal increases and decreases in stream water nutrient concentrations has been observed in the Pacific Northwest and elsewhere (Edmonds et al., 1995; Feller, 1979; Vitousek and Reiners, 1975; Stoddard, 1994). This pattern depends on several factors including dominant vegetation, soil characteristics, and rainfall (and snowfall) amounts.

The objective of this study is to quantify the pattern and extent of P and N export during runoff events before and after biosolids application. In addition to the possible influence of biosolids, several other factors controlling stream water nutrient concentrations and export may operate within the watershed studied including management impacts such as thinning, seasonal changes in vegetation and soil nutrient status, and soil mineral weathering.

Study Site Characteristics

The 27 Creek Watershed is located at the University of Washington's 1720-ha Charles Lathrop Pack Demonstration Forest. Pack Forest is at the base of the Cascade foothills about 110 km south of Seattle. Dominant vegetation on the forest is second growth Douglas fir with some western hemlock, western red cedar and red alder. The climate is typical maritime, with relatively dry summers, wet winters, and moderate temperatures throughout the year. Annual precipitation is about 120 cm, with approximately 50% falling in the period of October through January. Rainfall during the period of July through August is usually less than 12 cm, often resulting in drought-like conditions on well drained soils. For normal temperatures and precipitation, evapotranspiration is estimated between 38 to 56 cm annually.

Watershed Description

The study site is a 21.4-ha headwater watershed and is drained by a first-order perennial stream (27 Creek). The watershed ranges between 420 and 600 meters elevation, with a northwesterly aspect (Figure 1). Topography is steep, with some slopes exceeding 60%. Nearly all of the watershed was clear-cut in 1982 and replanted the following year, and it currently consists of 15-year-old second growth Douglas fir intermixed with naturally regenerated western hemlock and red alder. Most of the watershed was pre-commercially thinned in March and April 1996; and felled trees were left in place.

Watershed Soils

Soil within the 27 Creek Watershed was formed from weathered andesite and basalt and is mapped as the Wilkensen soil series (fine-loamy, mixed mesic Vitrandic Haploxeralfs). Along the 27 Creek corridor, soils have characteristics of the Scamman series, a poorly drained clayey glacial till (fine, mixed, mesic Aeric Glossaqualfs). Watershed soil chemical characteristics are shown in Table 1.

Table 1. 27 Creek watershed and King County biosolids chemical composition.

	NH_4^+-N	NO_3^--N	N	P	C	pH
	mg kg^{-1}		%			
27 Creek soil	22	6	0.13	0.03	3	4.2
King Co. biosolids	11200	11	7	2.5	34	8.7

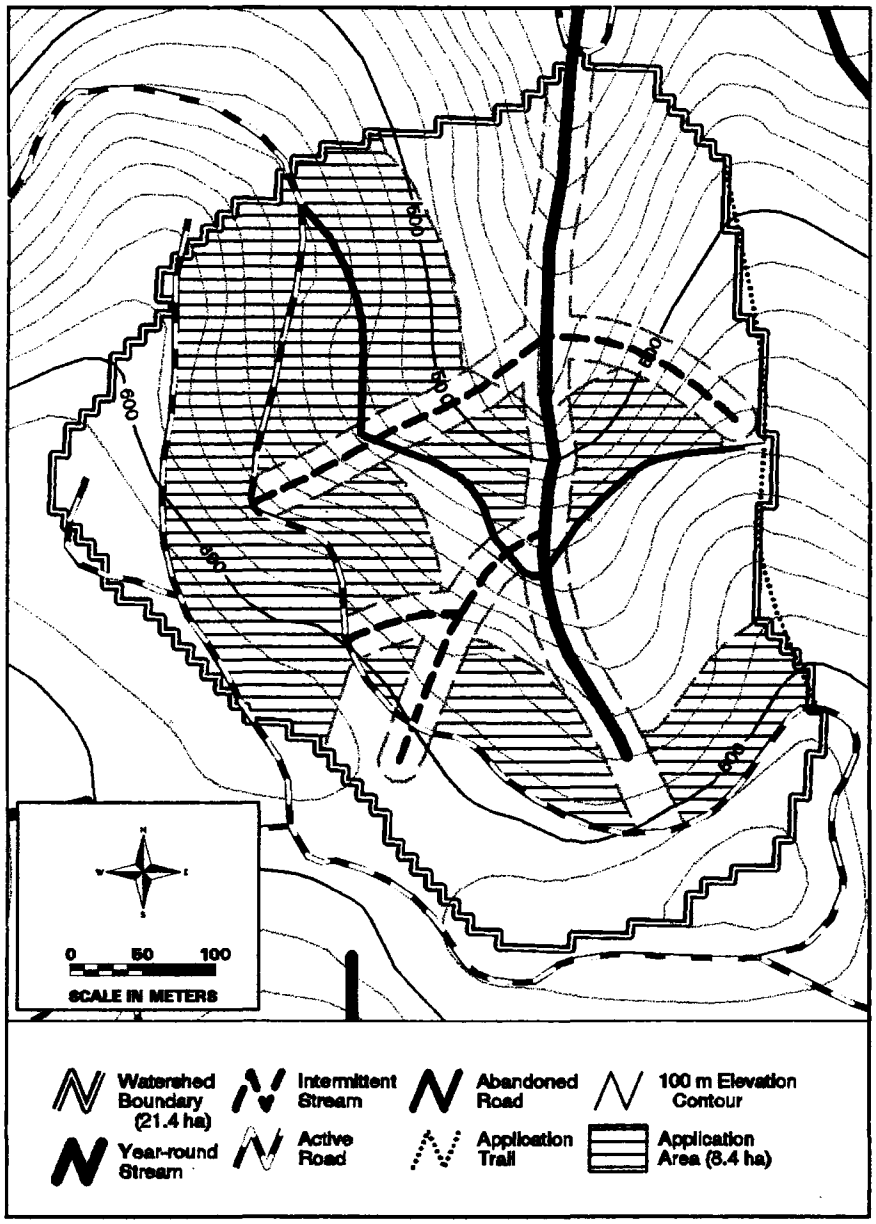

Figure 1. 27 Creek Watershed, Pack Forest, Washington.

Watershed Hydrology

Flow rates in 27 Creek are seasonally influenced and highly responsive to rainfall amount and duration. During wet weather months (October through April), flow rates vary between 75 and 10,000 L min^{-1}. The highest flow rate recorded to date followed a rain-on-snow event between December 26 and 29, 1996. During dry months, flow in the Creek has been recorded as low as 9 L min^{-1}. The Creek hydrograph during a runoff event generally follows the pattern of a steep rise (time to peak usually less than 12 hours, short peak duration of one to eight hours, and prolonged falling limb lasting two days or more).

Materials and Methods

Composition of Biosolids

Anaerobically digested, dewatered (20% solids) biosolids from King County's Renton Wastewater Treatment Plant was used; its chemical composition is shown in Table 1. Biosolids were applied to 8.4 of 21.4 hectares of the watershed during the third week of January 1997 and the first week of May 1997 to the hatched areas shown in Figure 1 at a rate of 13.5 Mg ha^{-1}.

27 Creek Flow Measurement and Water Quality Sampling

Automated flow recording and water sample collection devices were used to measure 27 Creek flow rate and to collect water samples during several runoff events before and after biosolids application. From November 1995 until present, water samples have been removed at least once a month by taking a grab sample at a single point in the Creek, followed by analysis for total P and total N. Beginning in October 1996, rainfall events causing a substantial rise in the stream hydrograph initiated automatic water sampling. After sampler initiation, water samples remained in the automatic sampler on ice until removal and transport to the King County Water and Land Resources Division Environmental Laboratory.

Analytical Methods

Total N and P as well as PO_4-P, NH_3-N, NO_3^--N were determined using standard methods for the examination of water (Standard Methods for the Examination of Water and Wastewater, 18th ed.). Biologically available P (BAP) was determined by filtering a known volume of creek water (0.45μm filter) and analyzing the extract for orthophosphate (Standard Methods for the Examination of Water and Wastewater, 18th ed., 4500-P, F). The material caught on the filter paper is extracted in a dilute sodium hydroxide/sodium chloride solution overnight, neutralized, filtered, and analyzed for orthophosphate. The sum of both determinations is BAP.

Soil and biosolids NH_4^+-N and NO_3^--N were extracted using 2.0 M KCl, then analyzed on a Technicon Autoanalyzer (Technicon Industrial Method No. 158-71W, 1977). Total N and C were determined by dry combustion (Perkin-Elmer CHN Analyzer Model 2400). Total P was determined using a HNO_3-H_2O_2-HCl acid digestion (EPA Standard Method 3050) and inductively coupled argon plasma spectroscopy (EPA Standard Method 6010. ICP; Thermo Jarrel Ash ICAP 61E, Thermo Jarrel Ash, Franklin, MA). Soil and biosolids pH were determined using a VFR model 3000 pH meter. A 1:2 soil/biosolids-distilled deionized water ratio was used with an equilibration time of 30 minutes before pH measurement.

Results and Discussion

Background Water Quality

Total N and P concentrations in 27 Creek between November 1995 and January 1998 are shown in Figure 2. Total P concentrations vary little, from 0.05 to 0.1 mg L^{-1}, while total N fluctuates much more, between 0.1 and 1. 5 mg L^{-1}. Total N concentrations in 27 Creek are higher after biosolids application as expected and seasonal fluctuations are evident, with the highest N concentrations recorded during late autumn. Background total P concentrations do not appear to be strongly influenced by seasonal changes or by biosolids application.

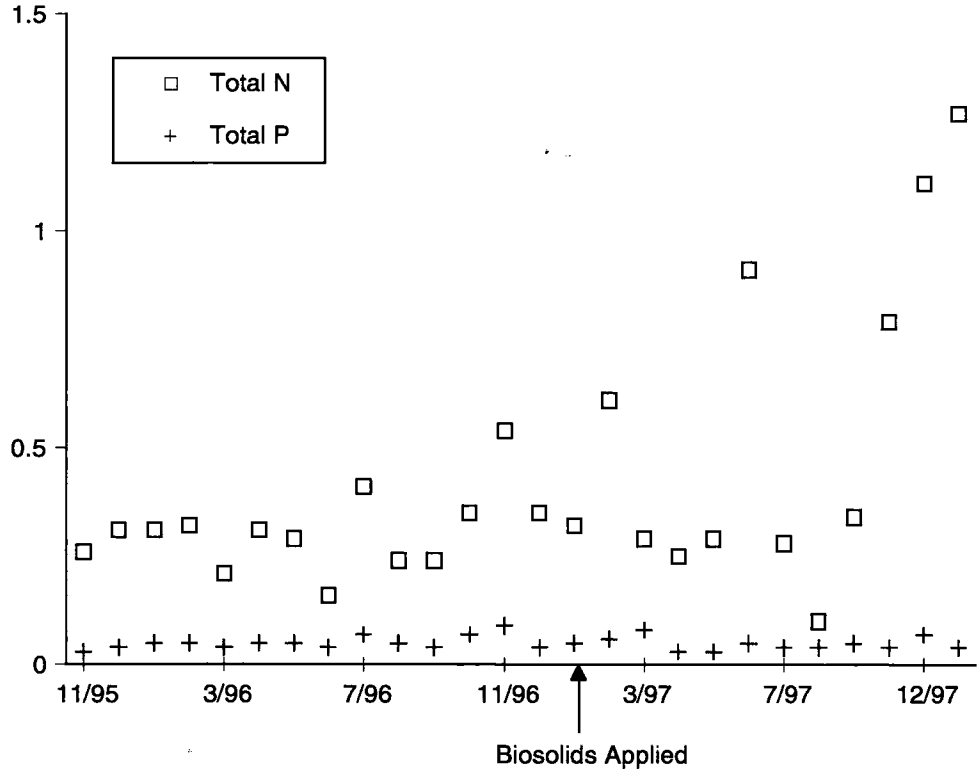

Figure 2. Total N and P in 27 Creek, November 1995 to January 1998.

Storm Runoff Conditions

Several rain storms and ensuing runoff events during 1996–97 and 1997–98 were monitored. Those rainfall events that produced a pronounced rise, peak, and fall of the 27 Creek hydrograph were selected for analysis and water samples removed throughout the hydrograph. Sampling during some runoff events was not done throughout the hydrograph and these cases are noted.

Dissolved Phosphate and BAP

From October 1996 to December 1997, PO_4-P and BAP concentrations showed little to no trends in response to rising or falling 27 Creek hydrographs for several runoff events (Figures 3–7). For brevity, two events prior to biosolids application in autumn 1996 and three events after it are shown. Runoff events in January and March 1997 (Figures 5 and 6) followed biosolids application by one week and two months, respectively; labile P concentrations during these events are equal to or below pre-application levels. Despite sampling primarily the hydrograph rise during the January 1997 event, the results suggest no occurrence of a "first-flush" P runoff effect due to biosolids application. The March 1997 runoff event produced consistent P concentrations over a range of flow rates (Figure 6). A comparison of autumn 1996 events with those of autumn 1997 (Figures 3–4 vs. Figure 7) suggest that biosolids application has done little to change runoff event concentrations of labile P.

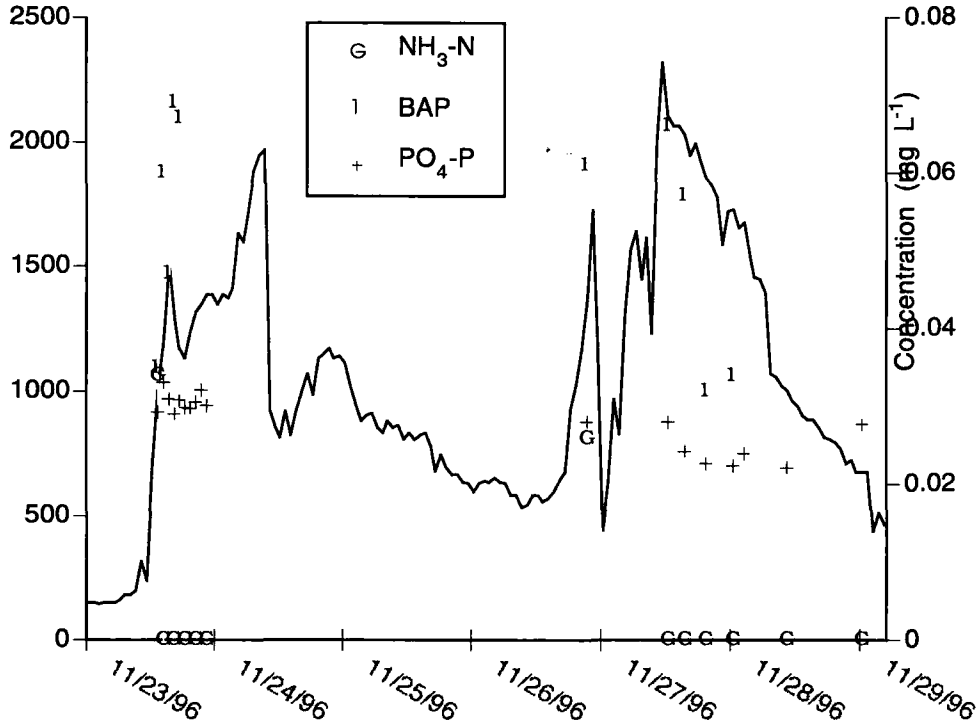

Figure 3. Ammonia-N, Phosphate-P and BAP in 27 Creek, November 1996.

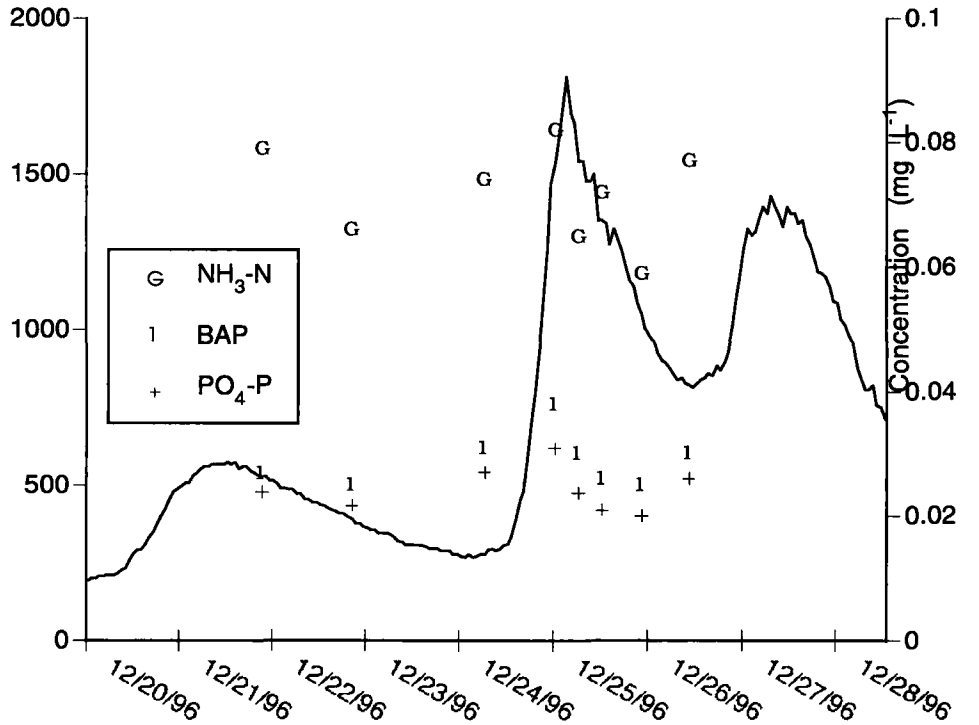

Figure 4. Ammonia-N, Phosphate-P and BAP in 27 Creek, December 1996.

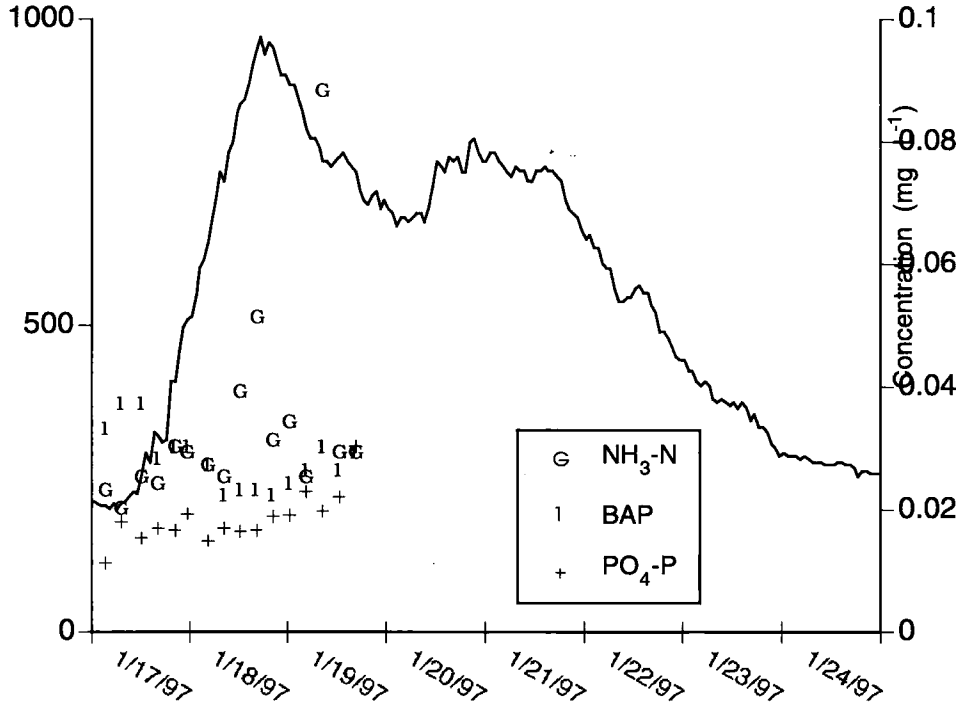

Figure 5. Ammonia-N, Phosphate-P and BAP in 27 Creek, January 1997.

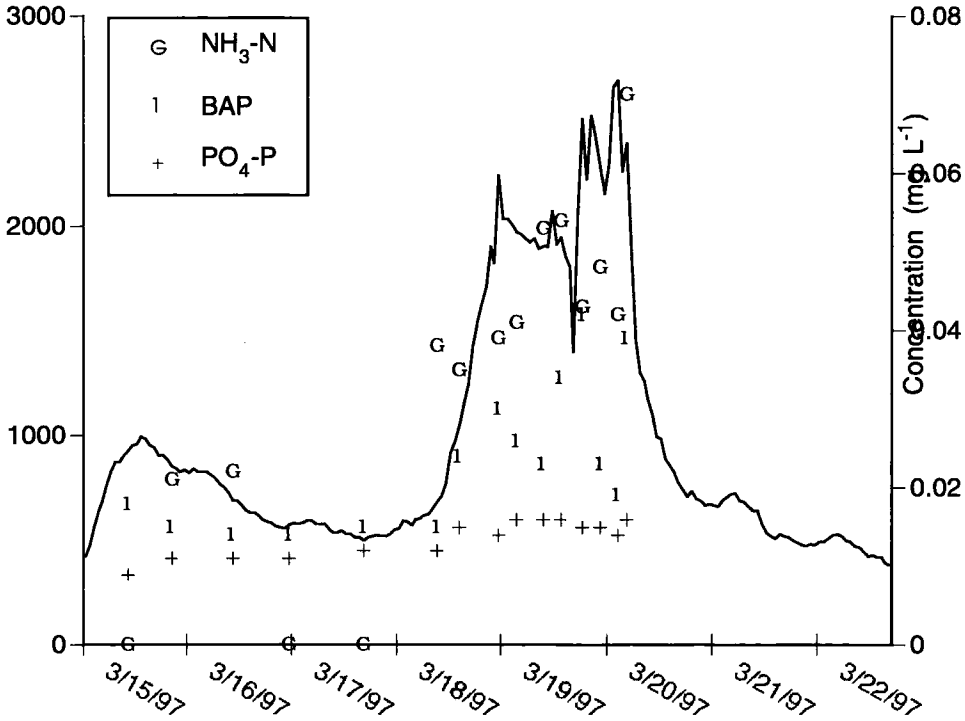

Figure 6. Ammonia-N, Phosphate-P and BAP in 27 Creek, March 1997.

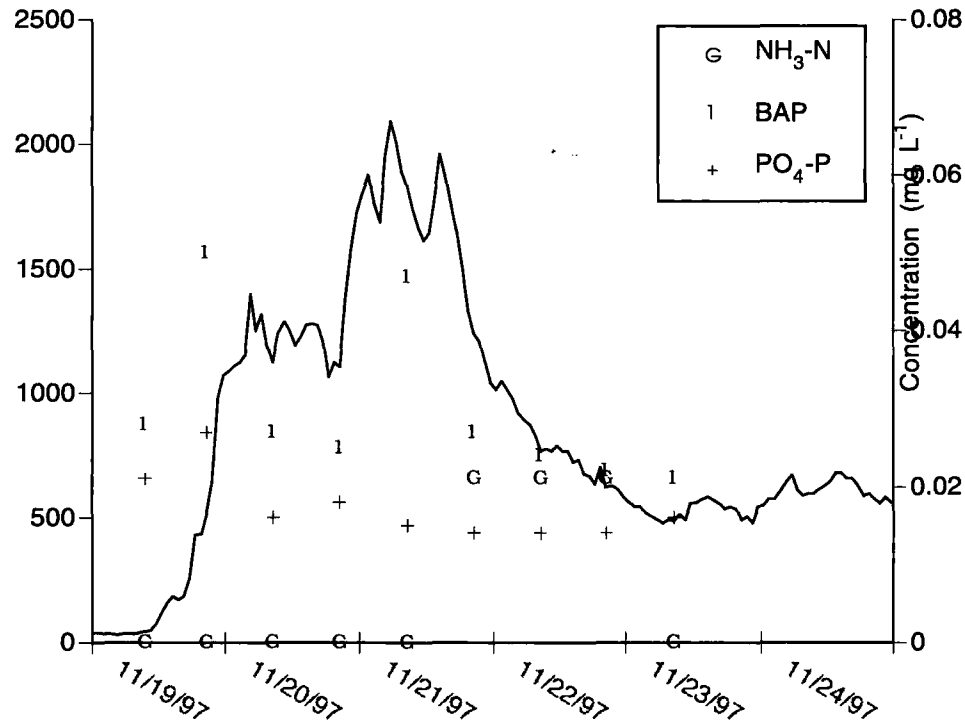

Figure 7. Ammonia-N, Phosphate-P and BAP in 27 Creek, November 1997.

Flow-weighted PO_4-P and BAP concentrations in 27 Creek have been consistent over the whole study period as well (Table 2). PO_4-P concentrations peaked in early October 1996 at 0.07 mg L^{-1} but dropped markedly after this and remained relatively constant between 0.01 to 0.05 mg L^{-1} over the study period. BAP in 27 Creek reflects a similar, but slightly larger concentration range. Flow-weighted total P concentrations fluctuate, with increased concentrations noted on two occasions after biosolids application. As labile P concentrations have not changed due to biosolids application, an increase in flow-weighted total P concentrations cannot be solely attributed to biosolids application. Organic matter input from the heavily vegetated stream corridor or in- or near-stream sediment P sources cannot be ruled out in contributing to total P in 27 Creek. Consistency in flow-weighted labile P concentrations before and after biosolids application strongly suggest that P transport from biosolids applications does not occur and P applied is conserved within the soil.

Dissolved PO_4-P and BAP concentrations fluctuate little during runoff event conditions, suggesting that labile P concentrations are not related to fluctuations in flow rate. In addition, biosolids application appears to have little influence on creek labile P concentrations or in changing the runoff event flow-concentration relationship. To check this assumption, PO_4-P and BAP concentrations recorded during runoff events were regressed against the flow rate at the time of sampling using both linear and non-linear regression techniques (Wilkinson, 1992). Analysis of the individual runoff events showed that flow rates explain little of the variation (r^2 <0.1) in creek PO_4-P concentrations over the range of flow rates recorded (data not shown). Pooling all of the data and separating pre-application from post-application concentrations gave comparable results (Figures 8 and 9). Data transformation of flow rates and concentrations did not improve correlations.

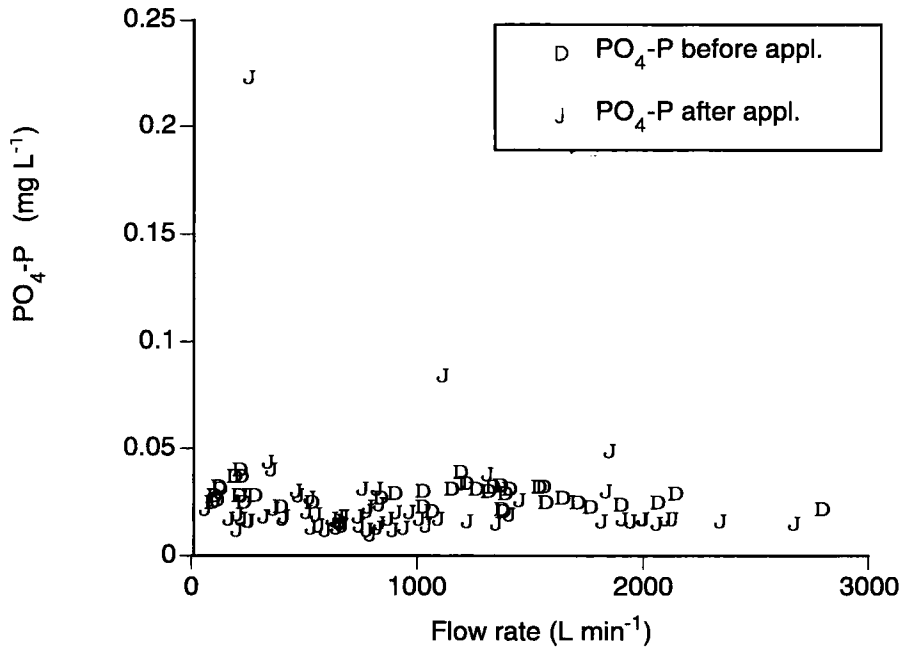

Figure 8. Dissolved phosphate vs. flow rate before and after biosolids application.

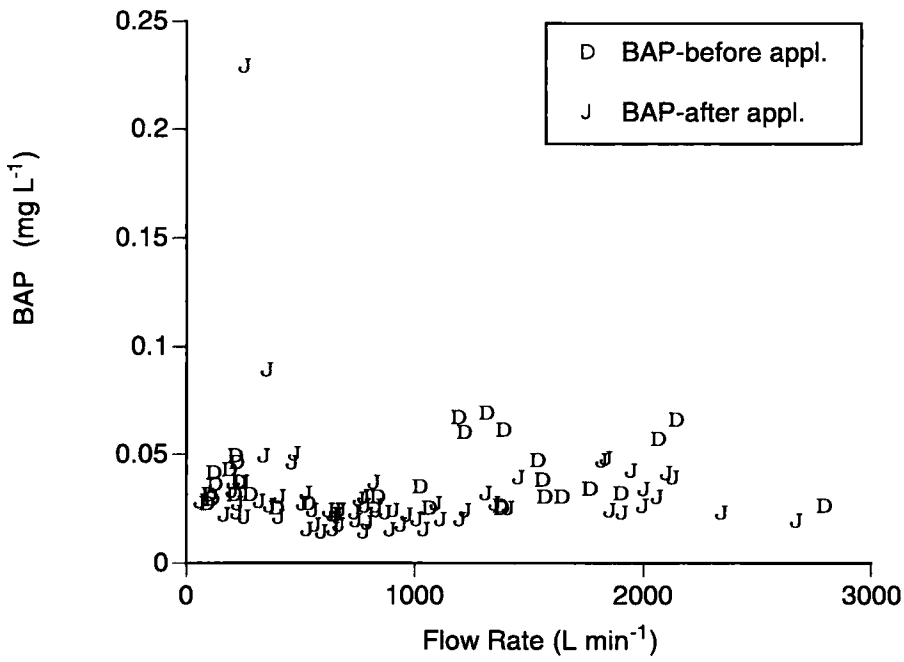

Figure 9. BAP vs. flow rate before and after biosolids application.

Ammonia and Nitrate

Flow-weighted ammonia-N (NH_3-N) concentrations, when detected, were low, averaging between 0.01 and 0.07 mg L^{-1} (Table 2).

Table 2. Average flow-weighted nutrient concentrations (nr = not recorded;. b = before application.

	PO_4-P	BAP	Total P	NH_3-N	NO_3^--N
Runoff Event	mg L^{-1}				
10/17–19/96b	0.03	nr	nr	nr	nr
10/23–25/96b	0.03	nr	nr	nr	nr
11/7–8/96b	0.03	0.03	0.05	nr	0.25
11/13–15/96b	0.03	0.04	0.08	nr	0.35
11/26–28/96b	0.03	0.05	nr	nr	0.35
12/20–28/96b	0.02	0.03	nr	0.07	0.23
12/31/96–1/3/97b	0.03	0.03	0.05	0.07	0.23
1/17–24/97	0.02	0.03	nr	0.04	0.21
3/15–3/22/97	0.01	0.03	0.09	0.04	0.18
5/31–6/4/97	0.04	0.05	0.32	0.07	0.27
10/31/–11/4/97	0.02	0.02	0.05	0.01	0.94
11/19–23/97	0.02	0.03	0.07	0.01	0.97
12/12–15/97	0.05	0.03	0.08	0.04	0.98
1/14–20/98	0.01	0.03	0.13	0.01	1.30

In approximately 40% of water samples taken for this study, ammonia concentrations have been below analytical detection limits (0.01 mg L^{-1}). During runoff events (Figures 3–7), NH_3-N concentrations generally fluctuate with changes in flow rate; some storms produced an apparent concentration-flow relationship. However, regression analysis of pooled NH_3-N data shows that flow rates are not a good predictor of NH_3-N concentrations in 27 Creek (Figure 10).

Ammonia-N concentrations in freshly applied biosolids are relatively high, ranging from 0.5 to 1.5% on a dry weight basis. Consequently, runoff waters directly contacting and moving through biosolids would be susceptible to high NH_4^+-N concentrations immediately after biosolids application. Conversely, NO_3^--N concentrations in anaerobically digested biosolids are often below 50 mg kg^{-1}. Therefore, in assessing changes in 27 Creek water quality, NH_3-N is a useful early indicator of possible effects of biosolids application on water quality, while NO_3^--N is useful over the long-term as biosolids decomposes and N mineralizes.

In the 1996–97 monitoring period, flow-weighted average NO_3^--N concentrations during runoff events were consistent, ranging between 0.18 and 0.35 mg L^{-1} (Table 2). This concentration range generally mirrors that found in precipitation (NADP, 1998). The five year (1992–96) average annual volume-weighted mean NO_3^--N concentration in precipitation is 0.34 mg L^{-1}. As with P, the highest concentrations noted in 27 Creek during the first year of runoff monitoring were recorded during October and November 1996 runoff events. Runoff event NO_3^--N concentrations fluctuated between 0.2 and 1.5 mg L^{-1} over the entire study period and generally no relationship was observed between flow rates and NO_3^--N concentrations (Figure 11).

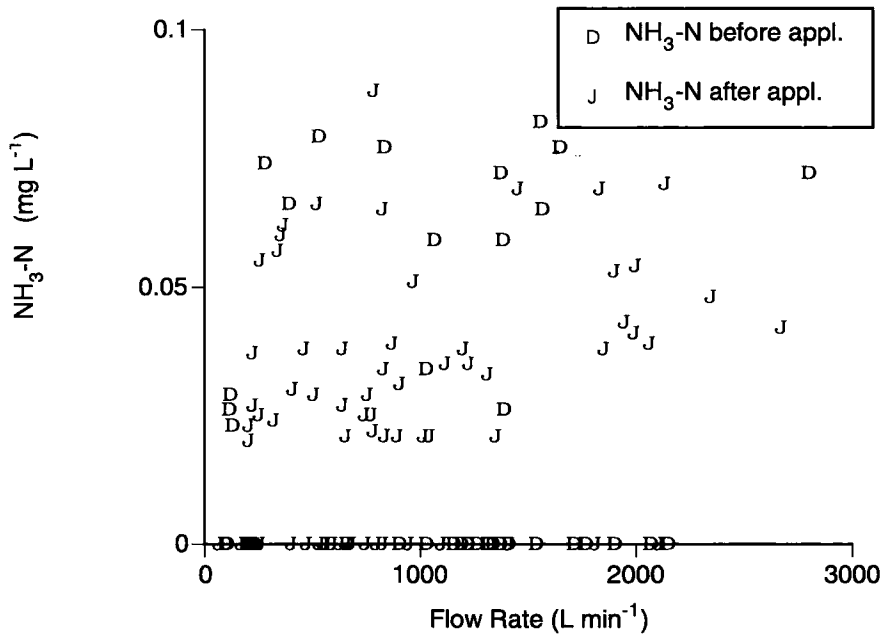

Figure 10. Ammonia-N vs. flow rate before and after biosolids application.

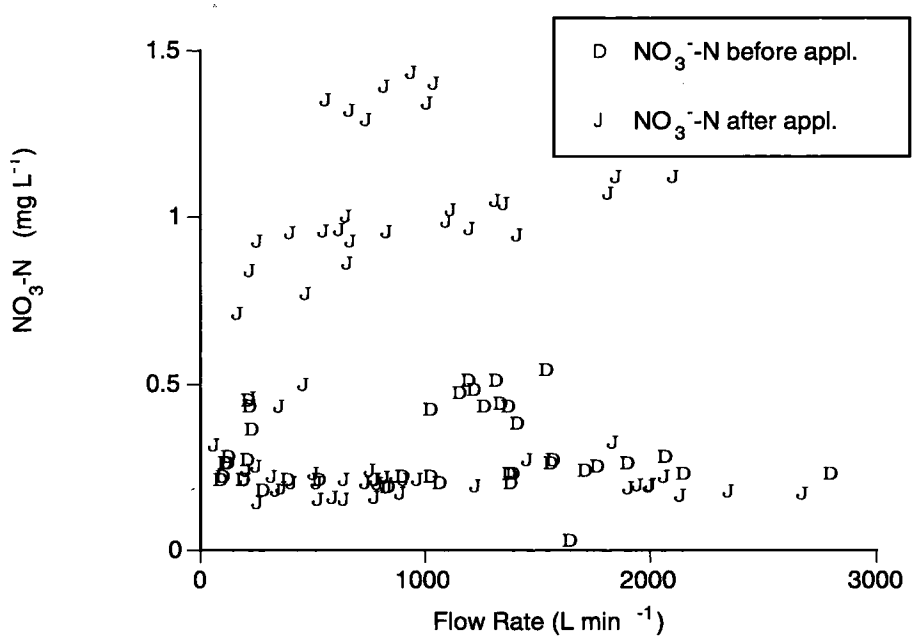

Figure 11. Nitrate-N vs. flow rate before and after biosolids application.

Beginning in late October 1997, the average flow-weighted NO_3^--N concentration noticeably increased to approximately 1 mg L^{-1} (Table 2). This is likely an effect of biosolids in increasing the soil-water NO_3^--N concentration due to organic matter and biosolids decomposition and N mineralization within the 27 Creek watershed. Nitrate-N concentrations in 27 Creek are well below drinking water standards, however. In general, NO_3^--N concentrations are greatest during late autumn months. This seasonal pattern of elevated nutrient concentrations during fall months is consistent with results from other watershed studies in the Pacific Northwest and British Columbia, and is often most pronounced for NO_3^--N (Edmonds et al., 1995; Feller, 1979).

Watershed Outputs of P and N

Watershed export of phosphorus and nitrogen for individual runoff events was determined by multiplying flow-weighted storm runoff event concentrations by the runoff volume. This value was then divided by the total watershed area and duration of the storm event to give an estimate of nutrient export on a g ha^{-1} day^{-1} basis. Table 3 shows the watershed export of nutrients for fourteen runoff events between October 1996 and January 1998.

Mass export of PO_4-P and BAP has been consistent over the two-year study period and there appears to be no effect of biosolids application on daily export during runoff events. In general, export of labile P forms is greatest in autumn and early winter, presumably due to decomposition following leaf and litter drop and subsequent mineralization of organic P. Pre-application runoff event nutrient mass export for PO_4-P and BAP peaked in November 1996 and declined two- and three-fold, respectively, before application. Peak export rates after application were noted in December 1997 for PO_4-P and November 1997 for BAP; mass export of both parameters declined in January 1998. The late November and December peaks in nutrient mass export during both monitoring seasons suggest there are seasonal controls on watershed export of labile P forms. Near creek soil and sediment P and organic debris input into the stream likely regulate PO_4-P and BAP concentrations in the creek and probably control total P concentrations as well.

Export of total P has increased over the runoff-event monitoring period, but relating the increase in total P export solely to biosolids may not be warranted. For example, PO_4-P and BAP export have been consistent over the monitoring period and no clear-cut effect of biosolids on export of either parameter has been noted. As BAP is a measure of labile P, the difference between it and total P suggests that resistant organic debris or sediments are contributing to the total P load in 27 Creek. The creek corridor is heavily laden with organic debris and deciduous and evergreen plants and this may explain some of the variation in total P export.

Table 3. 27 Creek watershed nutrient export (nr = not recorded; b = before application).

	PO_4-P	BAP	Total P	NH_3-N	NO_3^--N
Runoff Event	g ha^{-1} day^{-1}				
10/17–19/96b	0.1	nr	nr	nr	nr
10/23–25/96b	0.2	nr	nr	nr	nr
11/7–8/96b	0.2	0.2	0.4	nr	2
11/13–15/96b	0.5	0.6	1.3	nr	5
11/26–28/96b	2.2	4.0	nr	nr	27
12/20–28/96b	0.8	1.0	nr	2.3	7
12/31/96–1/3/97b	1.2	1.5	2.3	3.6	11
1/17–24/97	0.9	1.2	2.8	1.6	9
3/15–3/22/97	0.9	1.7	5.7	2.7	12
5/31–6/4/97	1.1	1.6	9.5	2.0	8
10/31/–11/4/97	0.3	0.5	0.9	0.03	19
11/19–23/97	1.1	2.1	4.9	0.6	66
12/12–15/97	2.7	nr	4.5	2.1	56
1/14–20/98	0.7	1.3	6.9	0.3	67

The nitrogen data show contrasting trends. Ammonia-N export has been steady over two monitoring seasons, suggesting that direct runoff from biosolids into receiving waters does not occur. In addition, the stable export rates along with a weak relationship between flow rate and NH_3-N concentration suggest that near-stream sources of NH_3-N influence stream concentrations and thus export. Ammonia-N export rates are highest in autumn months and during large runoff events (12/96 and 3/97). Peak NO_3^--N export occurred 11 months after biosolids application and was double the peak export before application. Biosolids elevate soil NO_3^--N levels as expected, and combined with seasonal increases in soil NO_3^--N, substantially increases export during autumn–winter runoff events.

Consistent flow-weighted labile P and ammonia-N concentrations and export on a g ha^{-1} day^{-1} basis in 27 Creek suggest that direct runoff from biosolids into receiving waters does not occur using modern application technologies and proper stream and ephemeral drainage buffering techniques. Large runoff events do not appear to change the pattern or amount of labile P or ammonia-N leaving the watershed. Seasonal effects such as changes in soil nutrient status due to organic matter decomposition and mineralization and creek corridor vegetation/sediment dynamics cannot be excluded as factors affecting 27 Creek nutrient concentrations or watershed mass export.

Conclusions

- Little relationship exists between 27 Creek flow rates and P or N concentrations.
- Flow-weighted concentrations of PO_4-P and BAP have been relatively constant over the study period, suggesting no effect from biosolids on Creek labile P. NH_3-N behaves similarly, with flow-weighted concentrations ranging from below detection limits to 0.07 mg L^{-1}.
- Flow weighted NO_3^--N concentrations noticeably increased after biosolids application. Nitrate-N concentrations recorded, however, are well below drinking water standards (<10 mg L^{-1}) and are typically below 1 mg L^{-1}.
- Peak mass export rates of PO_4-P and BAP were noted in autumn months with a general two-fold decline during winter and spring runoff events. Biosolids appears to have little effect on export rates of labile P. Total P export during runoff events has generally increased over the study.
- Ammonia-N export does not appear to be affected by biosolids application. Export was generally greatest in winter months.
- Peak NO_3^--N export occurred following biosolids application and was approximately two-fold greater than peak pre-application autumn export.

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An Investigation of Methyl Halide Levels in Lake Sammamish, Sammamish River, and Lake Washington, WA

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Introduction

The presence of holes in the ozone (O_3) layer has been highlighted by much media attention in the last few years. While 99% of the atmosphere is composed of N_2 and O_2, reactive trace gases present in parts per million (ppm) to parts per trillion (ppt) amounts play critical roles in atmospheric gases. There are several classes of trace gases that can cause ozone depletion; the methyl halides are an important source of ozone-depleting radicals. These radicals interrupt the equilibrium between O_2 and O_3 in O_3 formation, and serve to catalyze ozone-depletion.

Methyl chloride is the third-largest source of chlorine (Cl) after the chlorofluorocarbons (CFCs), CFC-12 and CFC-11. Currently, the amount of Cl in the air is estimated at 3800 ppt (Butler and Rodriguez, 1996). The majority of the Cl comes from the CFCs, but methyl chloride (CH_3Cl) does contribute to this amount. The average annual amount of CH_3Cl in clean background air is 620 ppt (Butler and Rodriguez, 1996). Unlike CFC-12, which has an average lifetime of 140 years, CH_3Cl has a short lifetime of 1–2 yr (Butler and Rodriguez, 1996). The principal sources of CH_3Cl are natural: oceanic emissions and fires. CH_3Cl's main sink is tropospheric oxidation with the hydroxyl radical.

Much more is known about methyl bromide (CH_3Br). CH_3Br is the largest carrier of stratospheric bromide (Br). The average annual amount in background air is 10 ppt, with a 1.3 northern hemisphere (NH)/southern hemisphere (SH) gradient (Butler and Rodriguez, 1996). Uncertainty still exists regarding the lifetime of CH_3Br, but it is short, approximately one year. The main natural source of CH_3Br comes from oceanic emissions from algae and phytoplankton. Biomass burning accounts for another natural source of CH_3Br. The rest of the principal sources of CH_3Br are anthropogenic: agricultural applications, leaded gasoline, combustion, and structural fumigation. Principal sinks of CH_3Br are: atmospheric reaction with ·OH, Cl·, and NO_3; photolysis; dissolution in seawater; and hydrolysis reaction with Cl- (Butler and Rodriguez, 1996).

Research has focused more intently on CH_3Br than on CH_3Cl because Br cycles more rapidly through the environment than Cl. On an atom-per-atom basis, Br is 50 times more effective than Cl in removing stratospheric ozone. While a smaller amount of Br is present in the stratosphere, 10 ppt of CH_3Br would be equivalent to 500 ppt of Cl, making Br a considerable factor in ozone depletion. In fact, it is estimated that 20–25% of the annual Antarctic ozone hole is caused by Br-catalyzed destruction of ozone, which occurs through the following proposed mechanism (Huang, 1997):

(1)

$$\begin{array}{l} Br\cdot + O_3 \rightarrow BrO\cdot + O_2 \\ Cl\cdot + O_3 \rightarrow ClO\cdot + O_2 \\ BrO\cdot + ClO\cdot \rightarrow Br\cdot + Cl\cdot + O_2 \\ \hline 2O_3 \rightarrow 3O_2 \end{array}$$

Unlike the CFCs, which are anthropogenic in origin, CH_3Br is produced both naturally and anthropogenically. An abundant amount of research has been devoted to finding the precise budget for CH_3Br sources and sinks because the effectiveness of restrictions on man-made CH_3Br sources on ozone depletion must be determined. Currently, the 1992 Copenhagen Amendments to the 1987 Montreal Protocol between industrialized and developing nations states that the production of CH_3Br in industrialized nations has been frozen to 1991 levels; production of CH_3Br will be phased-out of industrialized nations by the year 2000. Developing nations have 10 more years to phase-out CH_3Br production (Butler and Rodriguez, 1996). Fortunately, since CH_3Br has a short lifetime, the effects of these restrictions should cause a notable reduction in stratospheric Br in less than a decade after cessation of anthropogenic emissions. This differs considerably from the long-lived CFCs: even if all CFC emissions were stopped, half of the CFC-12 present today would still reside in the atmosphere in 100 years (Butler and Rodriguez, 1996).

To determine whether restrictions on anthropogenic methyl halide use would significantly impact the Puget Sound region, levels of methyl bromide and methyl chloride were measured in Lake Sammamish, Sammamish River, and Lake Washington in order to ascertain whether any point-sources of methyl halides that were anthropogenic in origin existed.

Materials and Methods

Air samples were pumped into Rasmussen or Krasnik air canisters, using a battery-powered diaphragm pump. Water samples were obtained in 100-mL glass syringes. All samples were taken several inches below the surface. Lake Sammamish samples were taken at least 20 meters away from the shore; Sammamish River samples were taken 1–3 m away from the shore; Lake Washington samples at Log Boom County Park and Juanita Beach County Park were taken approximately 100 m from the shore.

An extraction board that utilized cryotrapping was used to concentrate sample gases. The trap used to concentrate the methyl halides was packed with 5 cm of glass wool, followed by 5 cm of Porasil C (80/100 mesh), 5 cm of Porapak T (80/100 mesh) and 5 cm of glass wool. Air samples were injected into the board and were concentrated in the trap for 4 minutes at –40° C by immersion into a Dewar flask containing ethanol cooled with dry ice. After concentration, the trap was heated to 100° C by immersion into a Dewar flask of boiling water, and the sample gases were injected into the HP 5890 Series 2 Gas Chromatography Instrument (Hewlett-Packard). Water samples were stripped of methyl halides by the N_2 carrier gas for eight minutes in the stripping chamber. The stripped samples proceeded into the trap as outlined above.

Sample components were separated by a 30-m x 0.52-mm DB-624 capillary pre-column followed by a 75-m x 0.52-mm DB-624 capillary main column (J & W Scientific Products). The pre-column allowed for backflushing of trap contents after the compounds of interest entered the main column. Eluting components were detected using an HP G1223A ECD (Hewlett-Packard). Chrom Perfect Direct® software was used to perform peak integration. Data was reduced using calculations described by Bullister and Weiss (Bullister and Weiss, 1988).

Results

Tables 1 and 2 show air measurement data. All air samples taken showed normal background levels for methyl bromide and methyl chloride. The average background level of CH_3Br is 10–12 ppt, while the average background level of CH_3Cl is 620 ppt.

Table 1. CH_3Br and CH_3Cl air measurements (7/31/97).

Location	CH_3Br (ppt)	CH_3Cl (ppt)
Log Boom County Park	11.0 ± 0.4	528 ± 21
Sammamish R. Turf Farm	11.4 ± 0.5	539 ± 22
Idylwood Park	11.9 ± 0.5	535 ± 21

Table 2. Summer and winter CH_3Br air measurements (9/2/97, 2/26/98).

Location	CH_3Br (ppt) 9/2/97	CH_3Br (ppt) 2/26/98
Log Boom County Park	9.0 ±0.4	11.0 ±0.4
Juanita Beach County Park	9.5 ±0.4	10.8 ±0.4

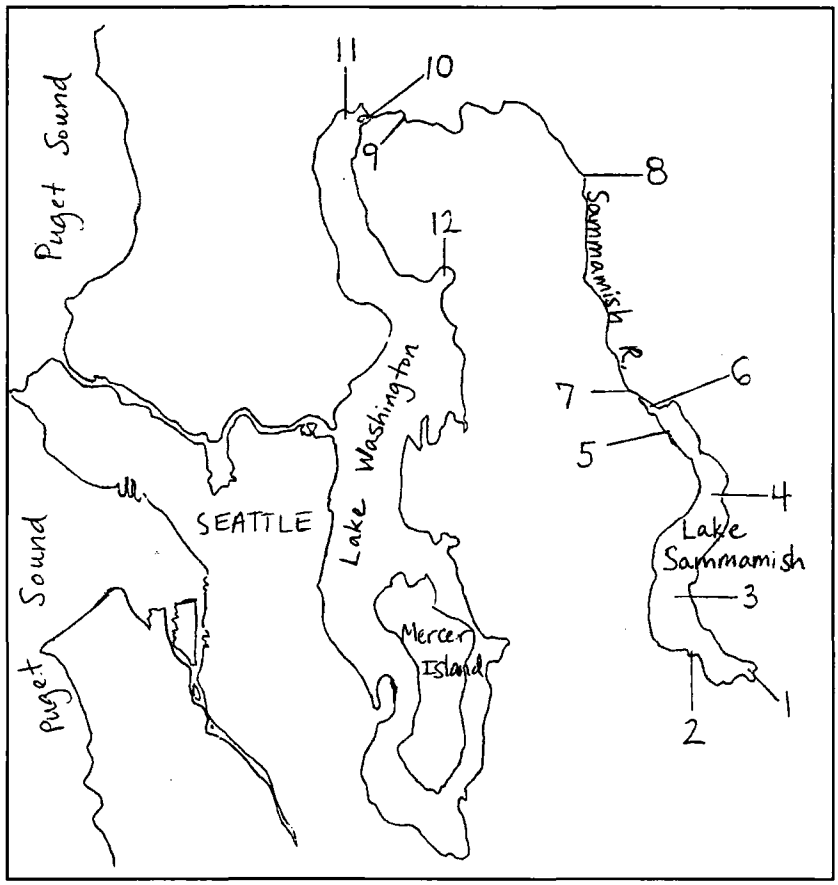

Figure 1. Sample site locations.

1) L. Sammamish/Issaquah Creek
2) L. Sammamish/Lewis Creek
3) L. Sammamish
4) L. Sammamish
5) L. Sammamish/Idylwood Park
6) L. Sammamish/Sammamish R.
7) Sammamish R./Marymoor Co. Park
8) Sammamish R./Turf Farms
9) Sammamish R./Swamp Creek
10) Sammamish R./Kenmore Boat Launch
11) L. Washington/Log Boom Co. Park
12) L. Washington/Juanita Beach Co. Park

Water samples of methyl bromide and methyl chloride were taken during the summer from Lake Sammamish, Sammamish River, and the north end of Lake Washington. Figure 1 shows a map of the locations where samples were obtained. Figure 2 shows the surface concentration of the methyl halide samples taken in the summer.

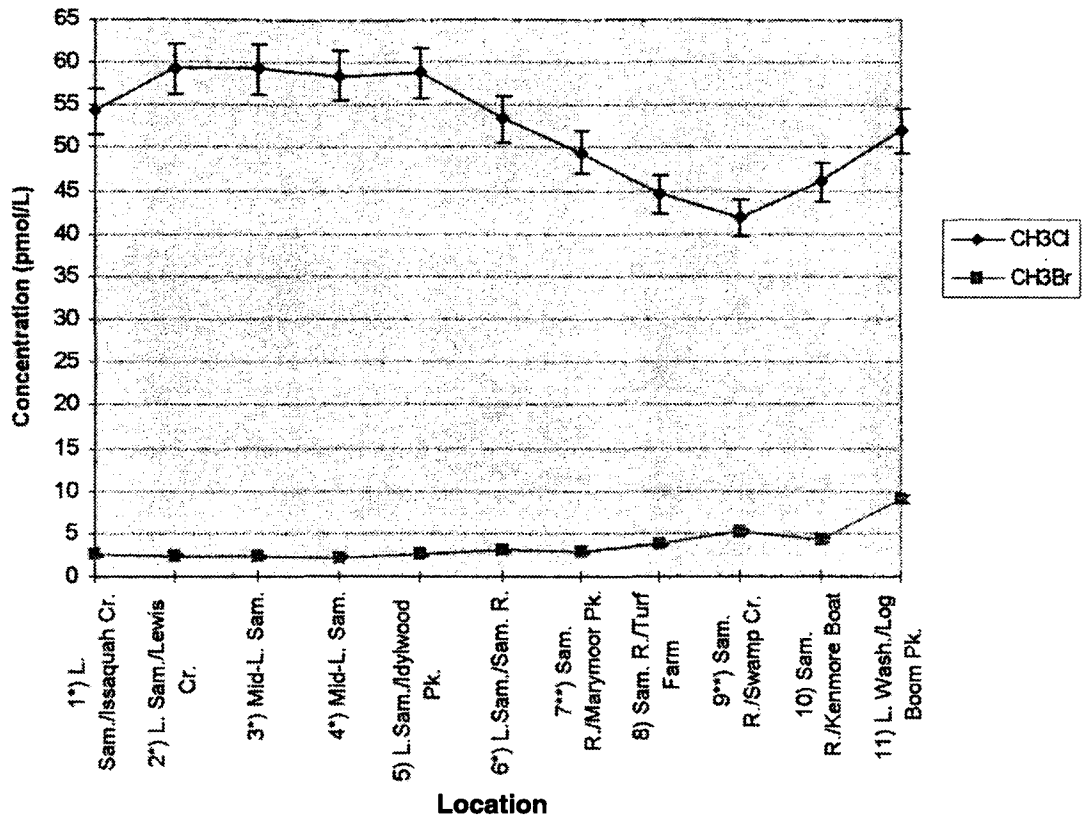

Figure 2. Methyl bromide and methyl chloride surface concentrations in Lake Sammamish, Sammamish River, and Lake Washington (7/31/97, 8/6/97*, 8/11/97**).

As shown from Figure 2, methyl bromide concentrations were low in Lake Sammamish and rose traveling along Sammamish River and the north end of Lake Washington. The concentration obtained at Log Boom County Park, CH_3Br = 9.06 ±0.45 pmol/L was quite high, approximately 3 times higher than the values obtained in Lake Sammamish. A value obtained from Madison Park, in the middle of Lake Washington, on 7/15/97 showed a CH_3Br concentration of 3.47 ±0.17 pmol/L, which was less than half the concentration of the value obtained at Log Boom County Park. Thus, further measurements comparing the CH_3Br values from Log Boom County Park and the similar, non-industrialized Juanita Beach County Park, were conducted to determine whether the high value obtained at Log Boom County Park was anthropogenic in origin.

The methyl chloride concentrations were highest in Lake Sammamish, approximately 60 pmol/L, and then decreased along the Sammamish River. The CH_3Cl concentration rose again at the end of the Sammamish River and the north end of Lake Washington, although the values did not rise to the same levels as were present in Lake Sammamish.

Figure 3 shows the summer-time saturation factors of CH_3Br and CH_3Cl seen at the sites. The trends follow those seen in Figure 2. All of the methyl bromide values show that the water was over 100% saturated. Very high levels of CH_3Br saturation were seen towards the end of Sammamish River and the north end of Lake Washington, with the saturation at Log Boom County Park greater than 400%. The methyl chloride saturation factor values seen in Lake Sammamish were approximately at equilibrium, and decreased below equilibrium in Sammamish River and the north end of Lake Washington.

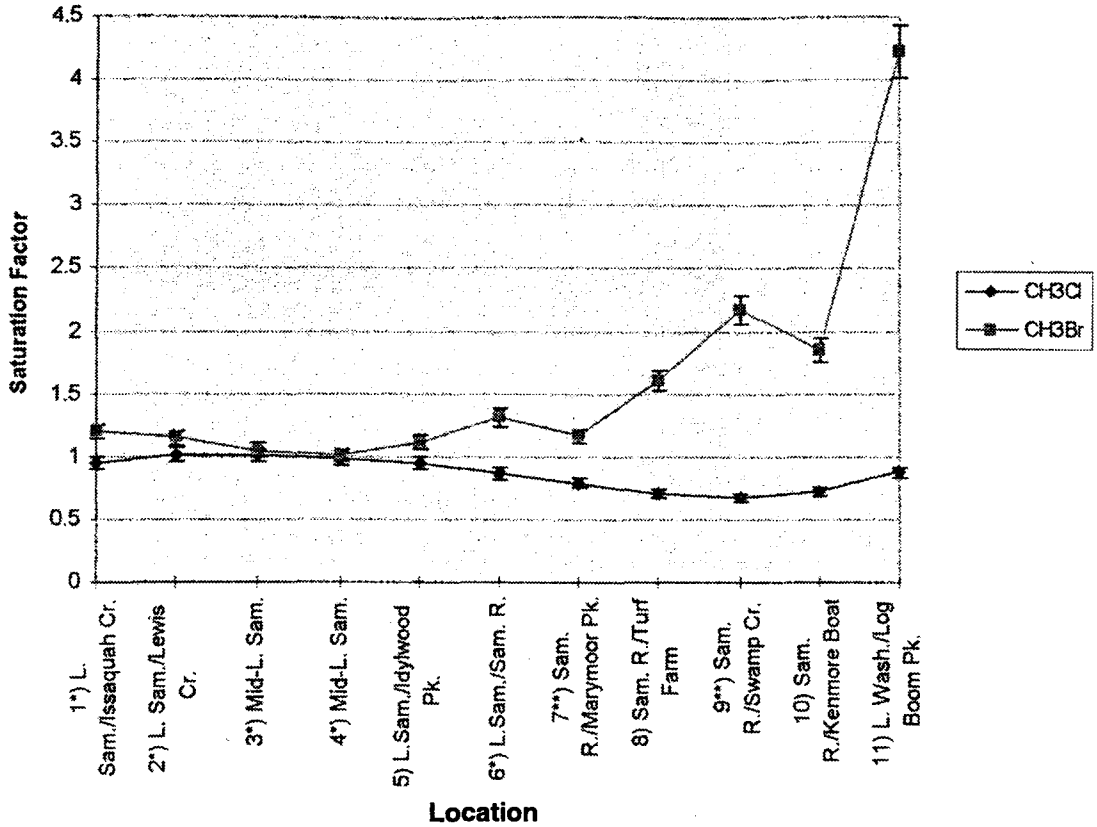

Figure 3. Methyl bromide and Methyl chloride surface saturation factors for Lake Sammamish, Sammamish River, and Lake Washington (7/31/97, 8/6/97*, 8/11/97**).

Figures 4 and 5 show the results for methyl bromide measurements taken at Log Boom County Park, Kenmore Boat Launch (at the end of Sammamish River), and Juanita Beach County Park. The measurements were conducted in summer and winter to determine whether the high sources of methyl bromide were anthropogenic or natural in origin.

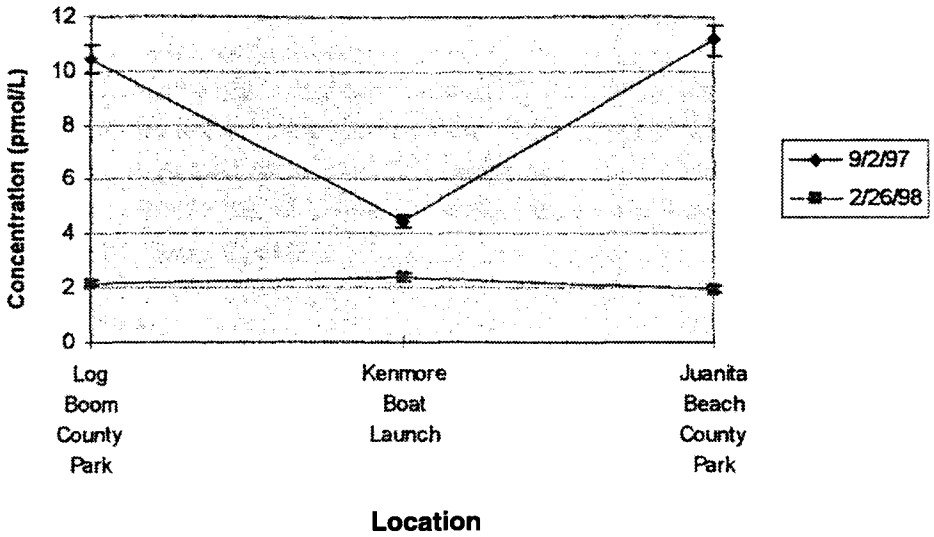

Figure 4. Washington and Sammamish River methyl bromide surface water concentration, summer vs. winter.

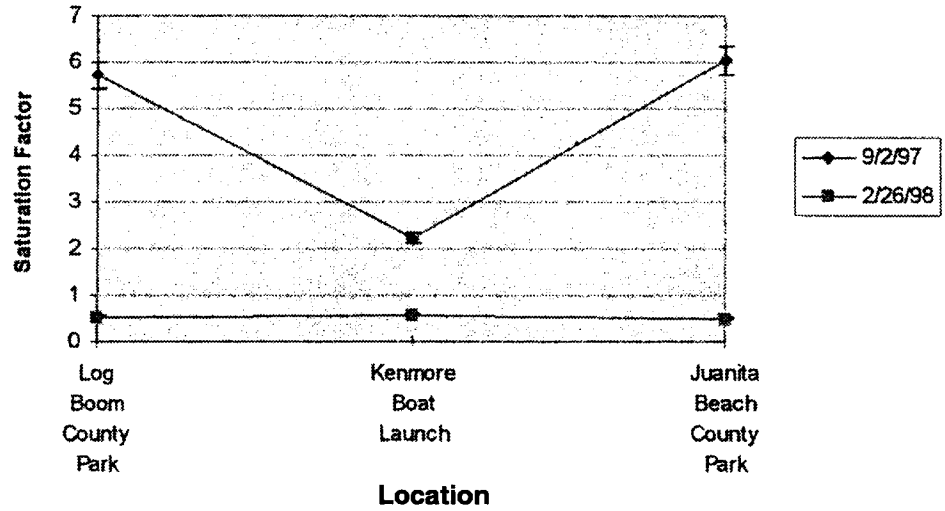

Figure 5. Methyl bromide surface saturation factors for summer vs. winter measures of Lake Washington and Sammamish River.

Figure 4 shows that in the summer-time, both Log Boom County Park and Juanita Beach County Park had comparable levels of methyl bromide, with CH_3Br concentrations at 10.4 ±0.5 pmol/L and 11.2 ±0.6 pmol/L, respectively. Figure 5 shows that both locations were highly saturated, over 500%. Interestingly, the summer-time CH_3Br concentration and saturation factor seen at the end of Sammamish River (near Kenmore Boat Launch) were less than half the values obtained at the two parks on Lake Washington, even though Kenmore Boat Launch is less than one mile away from Log Boom County Park.

The winter-time CH_3Br values at the same locations showed that the methyl bromide concentration at the two parks dropped considerably and were approximately equal to the concentration seen at the Kenmore Boat Launch, CH_3Br = 2.39 ±0.1 pmol/L. The saturation factor of the water was between 0.50–0.58, a marked decrease from the saturation levels seen during the summer. This decrease is consistent with the temperature-dependence of methyl bromide saturation. The surface water temperatures in the summer were between 22–24° C, while the surface water temperatures in the winter were approximately equal to 7° C.

Discussion

In terms of summer-time methyl chloride production, the environmental conditions in Lake Sammamish seemed slightly more favorable than those seen in the Sammamish River or in the north end of Lake Washington. The equilibrium values of the CH_3Cl saturation factors and the air measurements showing normal background levels of CH_3Cl, indicated that there were no unusually large point-sources of CH_3Cl.

The levels of CH_3Br seen along the Sammamish River, especially those near the turf farms, did not show unusually large values. If the turf farms used methyl bromide as a fumigant, it may be that the samples were not taken immediately after fumigation. Nevertheless, from the values obtained, it appeared that anthropogenic sources did not significantly contribute to the CH_3Br levels seen along the Sammamish River.

Industrial development exists around the Log Boom County Park area; however, since the summer-time levels of CH_3Br seen at Log Boom County Park were comparable to those seen at the non-industrialized Juanita Beach County Park, it can be concluded that the high levels were due to natural sources. Both sites experienced a dramatic drop in CH_3Br levels during the winter. If the high methyl bromide levels were from man-made activity, most likely the levels would not have

dropped so dramatically. These results confirm that the summer-time high levels of CH_3Br seen at the two parks were likely due to natural sources, such as algae and phytoplankton, which thrived in the warm, shallow waters of the parks. Thus, it does not appear that reduction of anthropogenic sources of methyl bromide will significantly alter the methyl bromide levels seen in Lake Sammamish, Sammamish River, or the northern end of Lake Washington.

Acknowledgments

I would like to acknowledge the NSF-REU program at the University of Washington for providing the funding which made my research possible. I would also like to thank Wenlin Huang and Dr. Richard Gammon for their assistance and guidance during the course of my research, and Dr. Kristen Skogerboe for her support throughout my undergraduate career.

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Total Maximum Daily Load Studies for Dissolved Oxygen and Fecal Coliform Bacteria in the Lower Skagit River

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Introduction

The Skagit River basin has a drainage area of approximately 3,093 square miles, which includes its headwaters in British Columbia. It is the largest basin tributary to Puget Sound, and the largest basin in Washington outside the Columbia River. The study area for this project is the lower Skagit River, which is the lowland portion of the river downstream from the lower end of Skiyou Slough near Sedro-Woolley. Just before the Skagit drains into Skagit Bay, it splits into the North and South Forks, which bound Fir Island. The Lower Skagit Study Area drains an area of about 200 square miles. Figure 1 presents a map of the study area.

The principal land uses in the study area are agriculture, forestry, and urban areas. Both dairy farming and row cropping are widespread in the study area. The three main population centers are Mount Vernon, Burlington, and Sedro-Woolley. Much of the study area is diked and drained, and several pump stations discharge water from the drainage districts into the Skagit River.

A water quality study was conducted in the lower Skagit River to evaluate the effects of point and nonpoint pollutant loading on dissolved oxygen (DO) and fecal coliform (FC) bacteria levels. Rapid growth in Skagit County has prompted concerns that increased wastewater discharges could degrade DO in the Skagit River. Low DO levels could contribute to impairment of Skagit River salmon. FC bacteria are an indicator of pathogens from sewage and manure. High FC levels could pose a public health threat to recreational users of the Skagit River, and could also degrade shellfish beds near the mouth of the river. FC bacteria levels historically have exceeded state standards in the Skagit River and its tributaries, and shellfish beds in Skagit Bay have been subject to harvest restrictions.

The Surface Water Quality Standards for Washington State are described in state regulations (Chapter 173-201A WAC). The Skagit River and its tributaries in the study area are subject to Class A fresh water Standards, with the exception of the upstream end of the study area (the Skagit River above Sedro-Woolley, at the lower end of Skiyou Slough), which is subject to Class AA standards. Skagit Bay is a Class A marine water, and the boundary between marine and freshwater standards occurs somewhere downstream of the study area.

If water quality standards are not being met or are threatened by existing pollutant sources, then a Total Daily Maximum Load (TMDL) may be established to regulate acceptable pollutant loads, as required under Section 303(d) of the Federal Clean Water Act. A TMDL technical study evaluates the combined effects of various sources in the basin to determine the loading capacity of pollutants that will protect the water quality standards and protect beneficial uses for the basin. Alternative TMDLs are recommended that may be allocated to point sources and nonpoint or background sources. The allocations may be implemented through NPDES permits, state waste discharge permits, grant projects, watershed action plans, and other nonpoint source control activities.

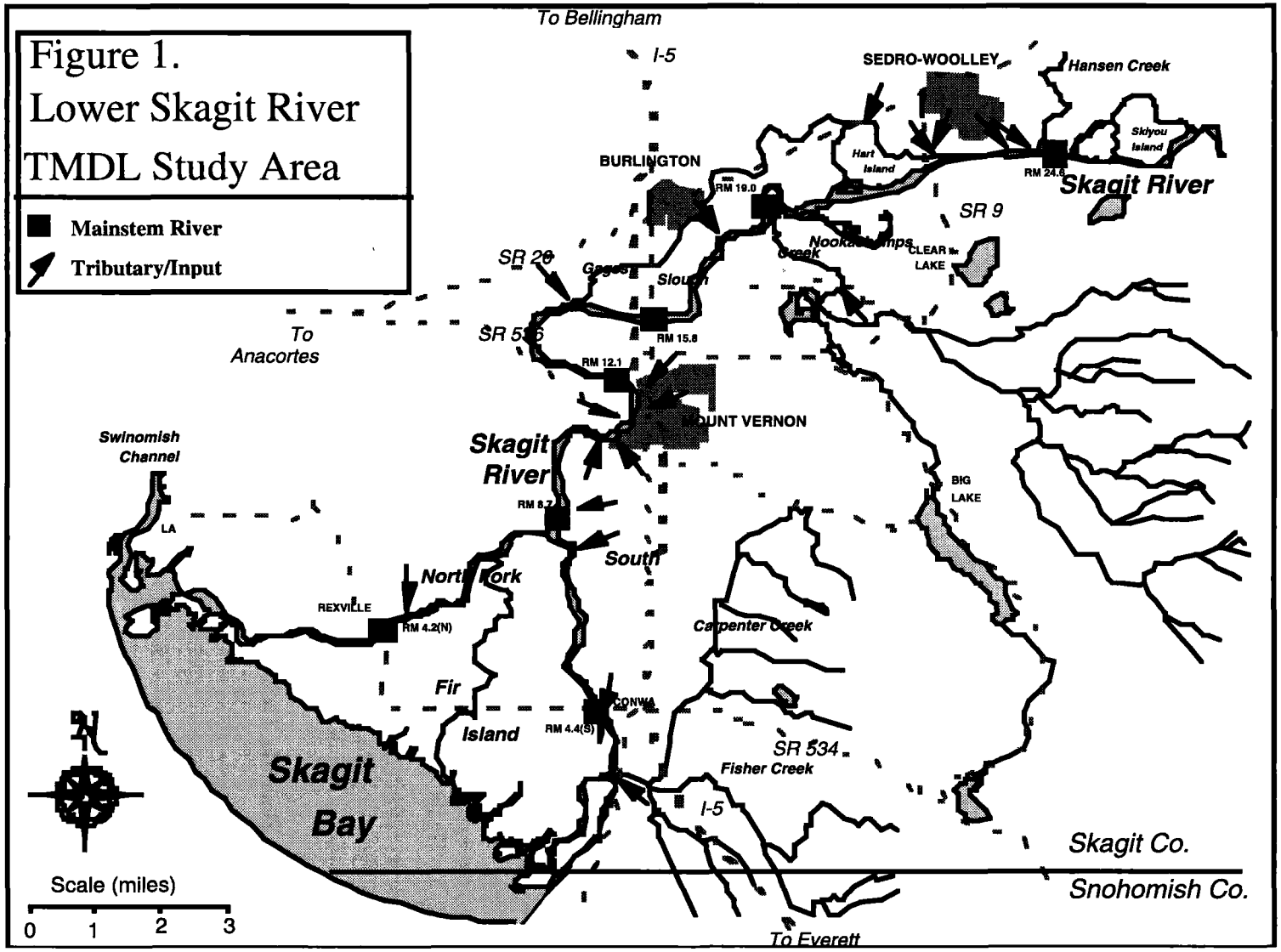

Figure 1. Study area in the lower Skagit River.

Study Description

Water quality surveys were conducted for 10 weeks from December 1994 through October 1995. The design for this study was described in detail in the Quality Assurance Project Plan (Pickett, 1995). Sampling sites, shown in Figure 1, included four municipal wastewater treatment plant discharges (Sedro-Woolley, Burlington, Mount Vernon, and Big Lake), tributary streams, drainage district pump stations, urban stormwater sources, and combined sewer overflows (CSOs). Surveys included samples for laboratory analysis, field measurements, and remote half-hourly measurements by multi-parameter data-loggers.

A summary of the data collected as part of this study was published in Pickett (1996). The data summary report includes complete tables of field measurements and laboratory analytical results. Pickett (1996) also gives a detailed summary of the data Quality Assurance/Quality Control analysis. A complete description of the TMDL analysis and results was published in Pickett (1997).

Dissolved Oxygen TMDL Analysis

The loading capacity of the lower Skagit River for Biochemical Oxygen Demand (BOD) was determined through computer modeling and other data analyses. HEC-RAS, a flow-routing model provided by the U.S. Army Corps of Engineers, was used for modeling velocity, time of travel, and the split of flow between the North and South Forks. Modeling of DO was done with Multi-SMP, a simple DO model developed under EPA contract. CORMIX was used to evaluate mixing effects near the Mount Vernon wastewater discharge and the split of pollutant loading from that discharge to the two forks.

The analysis of loading capacity produced the following results:

- The critical location for low DO in the lower Skagit River was found to be in the South Fork near Conway.
- TMDLs were proposed for carbonaceous BOD (CBOD) and ammonia. The Skagit River has the capacity to assimilate current design levels of CBOD and ammonia nitrogen from permitted point source discharges without violation of the dissolved oxygen water quality standards.
- The proposed TMDL provides capacity for future levels of CBOD and ammonia point source loading, if the allocations are met during the dry season critical low-flow period (July through October). Allocations to each point source are proposed based on 2015 effluent flows; ammonia nitrogen concentrations of 10 mg/L or current levels (whichever is less); and BOD concentrations of 20 mg/L. Figure 2 illustrates these proposed allocations.
- Effluent monitoring is recommended for ammonia nitrogen for all point sources. Ambient monitoring is recommended for DO in the South Fork Skagit River at the Conway bridge during neap high tide conditions.

Fecal Coliform Bacteria TMDL Analysis

The loading capacity of the lower Skagit River for FC bacteria was determined through modeling and data analyses with computer spreadsheets. Mass balances were developed for flow and FC bacteria for each survey. To predict flows for ungaged inputs, empirical relationships were developed from observed data. A first-order decay coefficient was applied to the FC mass balances. Unidentified sources were added to the FC mass balances where data indicated that those sources were present.

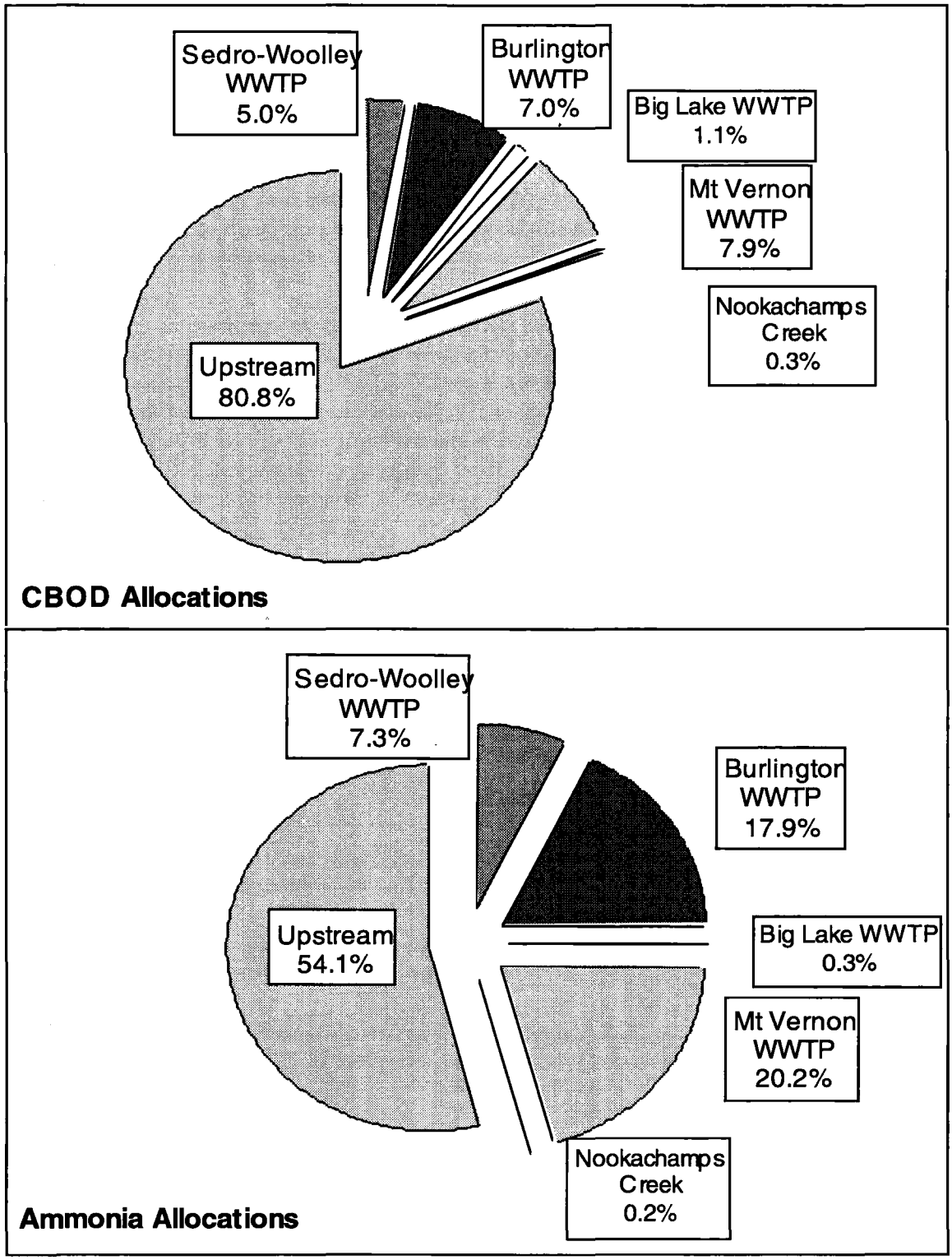

Figure 2. Lower Skagit TMDL CBOD and ammonia allocations (for 2015 Critical Conditions TMDL Alternative).

Using the mass balances and other data analyses, the loading capacity of the lower Skagit River for FC bacteria was determined and TMDLs were proposed to protect the water quality standards for FC bacteria. Target values for FC bacteria in the Skagit River were developed to ensure that marine water quality standards for FC bacteria would be met at the river's mouths. The FC bacteria analysis produced the following results:

- Current FC bacteria levels exceed Class A fresh water quality standards in many tributaries of the lower Skagit River, exceed Class AA standards in the Skagit River upstream of Sedro-Woolley, and very likely exceed the Class A marine standards at the mouths of the North and South Forks of the Skagit River.
- A FC bacteria TMDL is proposed in which marine water quality standards will be protected in Skagit Bay at the mouth of the Skagit River if the following conditions are met: 1) all permitted point sources meet their current permit limitations; 2) Mount Vernon CSOs discharge no more than once per year; 3) the Skagit River above Sedro-Woolley meets target values below the Class AA standards (6 cfu/100 mL geometric mean and less than 10% of values above 80 cfu/100 mL); 4) Nookachamps, Carpenter, and Fisher Creeks meet freshwater standards; and 5) loading sources at the Rexville pump station (Drainage District 15) and an unidentified source upstream of Kulshan Creek are significantly controlled.
- Addressing the long-term goal of having all tributary surface waters meet the Class A water quality standards will provide an additional margin of safety to the Skagit River and Skagit Bay. As resources allow, watershed plans and other nonpoint source control programs should be developed and fully implemented in watersheds, drainage districts, and other stormwater drainage areas that currently do not meet the standards.
- Long-term monitoring is necessary in the Skagit River (North and South Forks and above Sedro-Woolley) and in tributary waters to evaluate the FC bacteria TMDL.

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Integrating Watershed Management with Nonpoint Source Controls

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Introduction

This paper describes the current and past efforts of four local jurisdictions, King County, and the cities of Bellevue, Issaquah and Redmond, to manage nonpoint source inputs of phosphorus to Lake Sammamish. Lake Sammamish is a large urban lake located five miles east of Seattle, Washington in one of the most rapidly growing parts of the central Puget Sound basin (Figure 1). The management program for the lake is watershed based and uses an adaptive management strategy. Adaptive management is a process to improve the management of natural resources by allowing scientists and managers to incorporate new scientific knowledge and technological advances into a management program incrementally. This strategy integrates monitoring results, the output of a computer model that estimates the potential phosphorus control and annual costs of different management options for changing land use, and shared decision making to determine the most cost-effective management actions for implementation on an annual basis.

Historical Background

Lake Sammamish is used extensively for recreation by the more than 2 million people in the greater Seattle area. It provides rearing and migratory habitat to several species of anadromous fish including chinook and coho salmon, several warm water fish, and many types of wildlife. Phosphorus is the limiting nutrient in the lake (Welch et al., 1980). Phosphorus enters the lake from a variety of nonpoint sources including soil erosion associated with land disturbance and clearing, construction sites, landscaped gardens and commercial properties, animal wastes, failing septic tanks, and roads. Seasonally recurring blooms of *Cyanobacteria* and green algae appear to be related to both the annual loading of phosphorus into the lake and the meteorological conditions during a given year. Increases in the annual phosphorus loading to the lake result in increased concentrations of algae in the lake and decreased lake transparency (Perkins et al., 1997).

The lake has a long history of management for phosphorus control that began 30 years ago with the diversion of wastewater effluent and industrial inputs in 1968. Although total phosphorus concentrations in the lake gradually decreased during the ten years following this diversion, increased development of the watershed during the last 20 years has resulted in total phosphorus concentrations that produce bloom conditions during most summers. Typically the algae blooms reduce the lake's aesthetic qualities and its desirability for contact recreation. Little information exists as to the affect of the blooms on populations of fish and other organisms in the lake.

Lake Sammamish, which drains a 98 square mile watershed, includes four different jurisdictions as well as significant public lands (Figure 1). The jurisdictions include parts of the cities of Bellevue and Redmond, all of the City of Issaquah, and part of King County.

A management plan was developed by the four jurisdictions in 1989 (Entranco, 1989). Many of the recommendations of the plan were implemented by the four jurisdictions as part of an inter-local agreement signed by the governments in 1991. However, full implementation of the plan depended upon the development and evaluation of improved phosphorus control facilities, as well as the development, funding, and implementation of multiple nonpoint source control regulations and techniques.

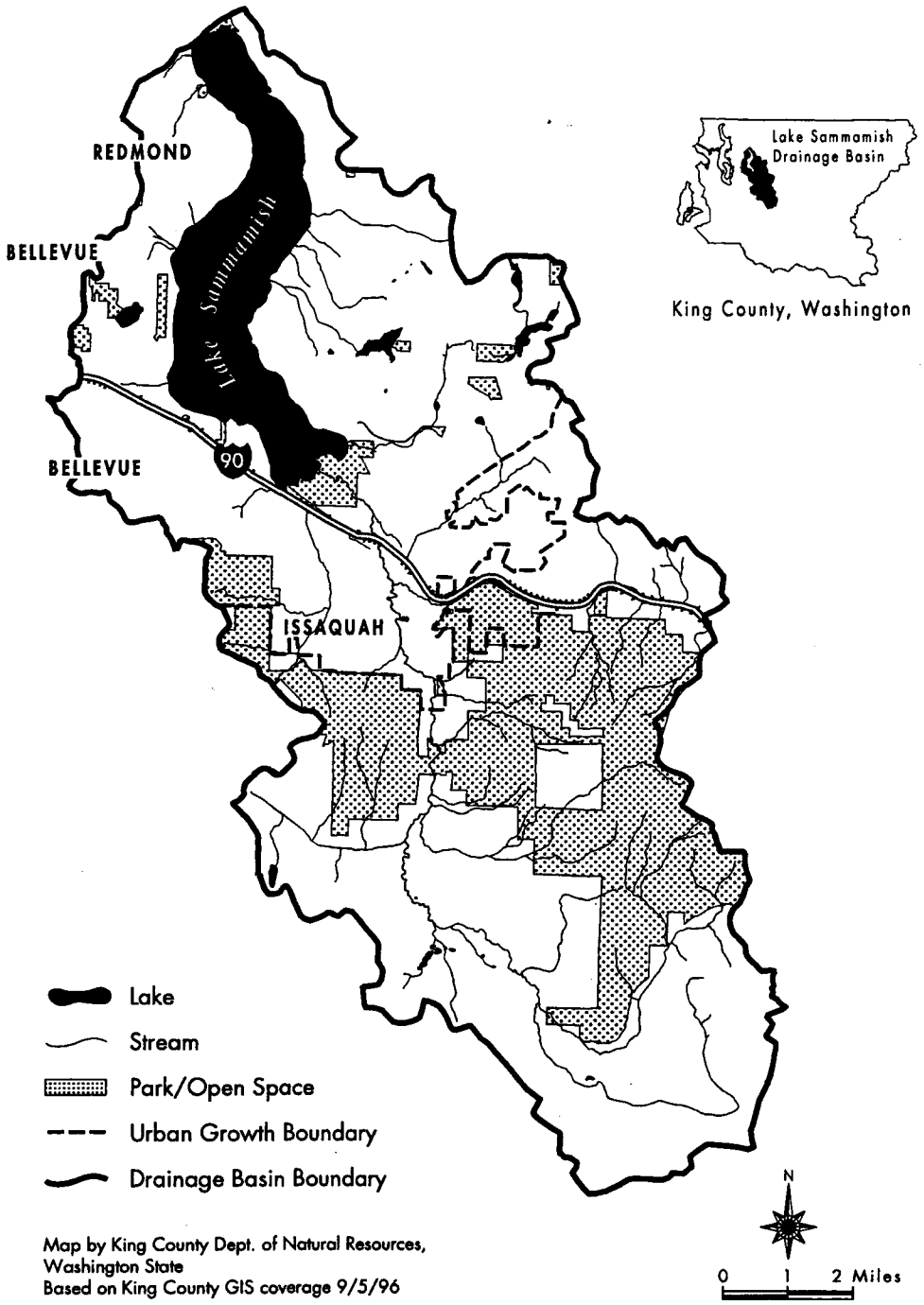

Figure 1. Lake Sammanish drainage basin.

While the development and evaluation of various phosphorus-control options took place, the lake's watershed continued to develop. Land-use changes in the watershed between 1985 and 1996 and predicted changes expected in the future based on current zoning are shown in Figure 2. In terms of phosphorus loading to the lake, the most significant change has been the conversion of forest land to single-family residential (SFR), and, to a lesser extent, multi-family (MFR) use and commercial use. In 1996, 77% of the annual phosphorus load was derived from SFR and MFR and commercial land use, although these land-use categories comprise only 46% of the watershed area (Entranco, 1996).

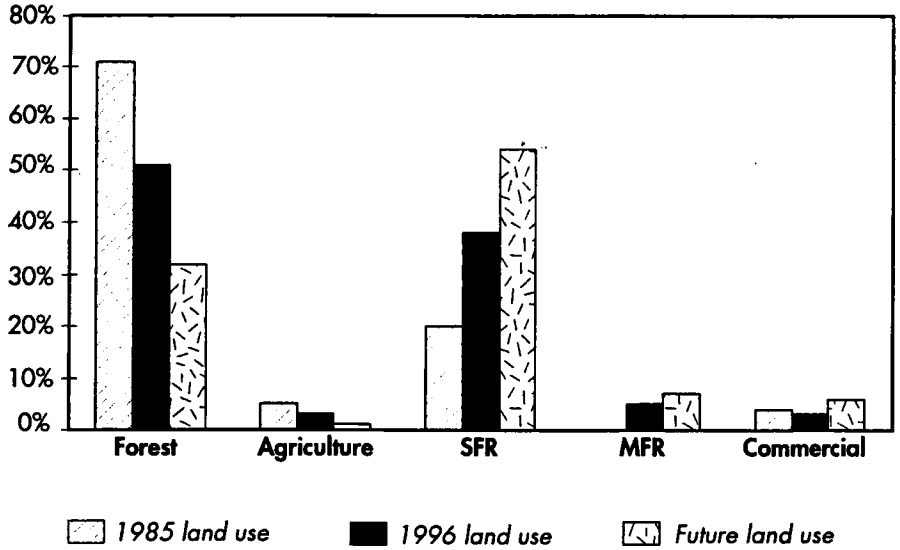

Figure 2. 1985, 1996, and future land use.

The 1996 Water Quality Management Plan

Based on a computer model, Perkins et al. (1997) predicted that the external phosphorus loading to the lake would increase above levels necessary to maintain the lake's water quality if the watershed continued to develop to its zoned capacity. In response, a citizen task force, Partners for a Clean Lake Sammamish (henceforth Partners), was appointed to review the water quality goals in the 1989 plan. Their charge was to identify cost-effective management options that would allow achievement of either the 1989 goals or new goals as defined by the community, and to identify costs and a financial plan for implementation.

The results of this effort showed that:

1. The community supported non-degradation water quality goals that maintained the current ecological health and public benefits of the lake;
2. Cost-effective management of nonpoint sources of phosphorus to the lake could likely be achieved by a multi-faceted program that uses new technology for phosphorus control facilities, an enhanced program for facilities maintenance, forest conservation, multiple programmatic and regulatory controls, and public acquisition of both upland and shoreline access parcels;
3. The costs of full implementation are large, including up to $2 million/year in public costs and up to $9 million/year in private costs for on-site water quality facilities, plus additional costs for acquisition of both shoreline access and upland public lands.

The management and financial recommendations developed by the citizen task force were submitted in July 1996 to an advisory forum of elected officials from the participating jurisdictions, the Sammamish Watershed Forum (Partners for a Clean Lake Sammamish, 1996). The Forum members supported the Plan's goals and strategy and recommended a combination of local and shared regional funding for its implementation. Specifically, the Forum recommended that the feasibility studies and public land acquisition should be paid for by shared regional funds while all other Plan recommendations should be funded by the four local governments, or by the private sector for on-site facilities for new development.

These recommendations and the analyses that supported them were summarized in the 1996 Water Quality Management Plan for Lake Sammamish (Entranco, 1996). The specific goal for the lake defined in the 1996 Plan is to protect the ecological health and public benefits of Lake Sammamish as described in the 1989 Lake Sammamish Water Quality Plan. The proposed measurements to confirm achievement of this goal are:

1. meters Secchi disk transparency (summer average)
2. μg/liter chlorophyll a (summer average)
3. μg/liter annual volume-weighted total phosphorus (These are the levels observed in summer 1995, and will be maintained through a management-tracking program for phosphorus inputs using the most cost effective measures available[i]).

The 1996 Plan's recommendations for achieving these goals were identified using a predictive computer model, WAQCEM, the Watershed Quality Cost Effectiveness Model. WAQCEM compared the feasibility, costs, and effectiveness of different management alternatives to control future increases in phosphorus loading to the lake from changes in land use (Richey et al., in press). The citizen task force used the WAQCEM results to identify a multi-faceted management program that was feasible, in terms of using available technology, being consistent with state and local regulations and social acceptability; and being cost-effective. The overall intent of the combined recommendations was to maintain annual phosphorus loading at 1995–96 levels, as demonstrated by maintaining the non-degradation goal indicator levels. The on-going monitoring program measures in-lake concentrations of total phosphorus, chlorophyll *a*, and lake transparency. The effectiveness of the management program can be evaluated on the basis the goal indicator levels are met on an annual basis.

The 1996 Plan recommendations took advantage of new technology for phosphorus control facilities that had been developed and tested since 1989 (King County, 1996; 1998a) as well as regulatory and programmatic controls that had been partially implemented as part of the 1989 Plan. A significant part of the 1996 Plan depended upon supporting and expanding a program of forest conservation which had been mandated in a Basin Plan adopted for the Issaquah Creek sub-drainage basin in 1995 (King County, 1995, 1998b).

The Plan depends upon each different management option to achieve roughly the following percentage shares of eliminating the future predicted increase in phosphorus loading to the lake:

1. Twenty-five percent—a requirement that all new urban developments build on-site stormwater facilities that control 50% of the total phosphorus generated by the newly developed sites;
2. Twenty percent—nonpoint source control programs for best management practices to reduce the use and export of phosphorus and sediments from homes, gardens, businesses, pets, farms, forest, stormwater facilities and roadside ditches; and increased support for citizen stewardship and technical assistance programs for regulatory compliance in erosion control at construction sites, and regulations for steep slopes, riparian buffers and shorelines;
3. Forty percent—forest conservation program including support of re-vegetation, current use taxation programs, land conservation, best management practices, and enforcement of a 65% clearing limit for rural residential lots.

The remaining approximately 15% of the needed phosphorus control is expected to be attained through a combination of improved technology, increased support of nonpoint source control practices, and improved regulatory compliance during the years it will take to reach full development of the watershed. Depending upon the rate of urban development in the basin, the WAQCEM model predictions indicate that this additional level of phosphorus control will not be needed for fifteen or more years, assuming that the other controls are implemented now.

The Partners considered and rejected inclusion of two other phosphorus control strategies as part of the 1996 Plan. These were the development of regional stormwater treatment plants and the retrofitting of existing stormwater detention facilities for phosphorus control. The Partners felt that the difficulties of siting and permitting one or more regional stormwater treatment facilities combined with the lack of an existing financial mechanism for either public or private funding of such facilities offset their greater cost-effectiveness. Instead they recommended a further feasibility study. They rejected the option of retrofitting existing on-site facilities due to the high cost and limited amount of phosphorus control that would be achieved by this action.

Plan Implementation

The four jurisdictions supported the adaptive management strategy recommended by the citizen task force and the specific management recommendations. In particular, the adaptive management strategy is expected to help prevent delays in shifting the year-to-year management of the lake to respond to changes in the lake's water quality, land use in the watershed, technology, and the success or failure of different management options. As shown in Figure 3, the adaptive management strategy incorporates an iterative, annual evaluation of the effectiveness of different phosphorus control actions. Through in-lake monitoring, the strategy allows evaluation of the water quality goals for the lake based on quantitative indicators for chlorophyll a, total phosphorus, and lake transparency. The jurisdictions are developing a process which will institutionalize annual or less frequent adjustments and changes to the overall management of the lake's water quality based on the monitoring program results, changing technology, and land-use change as quantified using the WAQCEM (or derivative) models.

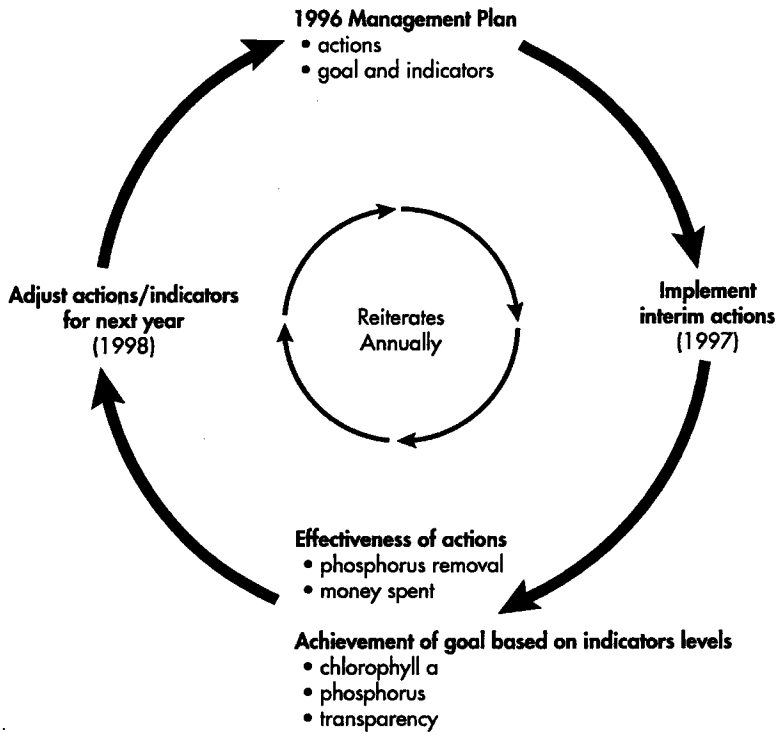

Figure 3. Lake Sammamish water-quality tracking program.
Note: cycle repeats for each incremental year.

Although there is no source of shared regional funds currently available in the area, the local governments funded implementation of parts of the plan during 1997 and 1998. Specifically, they supported the requirement for on-site water quality control facilities for new urban development throughout most of the watershed; the nonpoint source control and regulatory compliance support programs; and the forest conservation program. Parts of the enhanced maintenance program were funded, although some of the potential phosphorus control practices are being further evaluated prior to implementation. The local governments are also working to develop improved partnerships with state agencies in the watershed so that the various state agencies in the basin can focus on improving phosphorus control practices.

In accepting and funding the recommendations of the Plan, the jurisdictions recognize that there is a great deal of uncertainty associated with the effective implementation of nonpoint source control programs. Thus the assumptions built into the WAQCEM model are conservative and reflect low levels of participation on the part of citizens and businesses in most of the best management practices and typically half or less than half of the reported levels of phosphorus control for the different practices. The low levels of participation were felt to

be realistic given that, in the absence of financial or regulatory incentives, activities that require behavioral change on the part of thousands of individuals tend to occur very slowly.

The jurisdictions are supporting a wide range of outreach and public education programs as well as encouraging community groups and citizens to apply for stewardship grants for development of effective pilot programs. For example, citizens in one sub-drainage basin, Beaver Lake, received a grant to develop an outreach program and interpretive signs to encourage area residents to dispose of pet wastes properly so that the phosphorus they contain does not enter the surface waters.

Actual participation of citizens in residential best management practices is being evaluated through a series of public surveys that were started in the summer of 1997. It is hoped that the surveys will be extended to residents participating in the rural forest conservation program and the business programs. The monitoring of the actual effectiveness of the various controls will be dependent upon additional funding sources.

Monitoring of land-use change in the drainage basin is being evaluated through the updating of Geographic Information System (GIS) land-use data with development permit records. These updated GIS files will be used with the survey results in the WAQCEM model to determine, in conjunction with the in-lake water quality measures, if the various phosphorus controls should be modified or changed each year. It is expected that only minor changes will occur in the first few years since it takes time for citizens, businesses and public sector employees to change their day-to-day practices and for any changes to have an effect on phosphorus loading to the lake. For example, although total phosphorus concentrations in the lake during 1997 were slightly less than those observed in 1996 (Figure 4), this change is likely well within the year-to-year variability observed in the lake. It cannot yet be determined if there is any change in the phosphorus concentrations in the lake. The jurisdictions did not change management actions for 1998. It will take several years to determine whether or not there is a change in the overall water quality conditions in the lake.

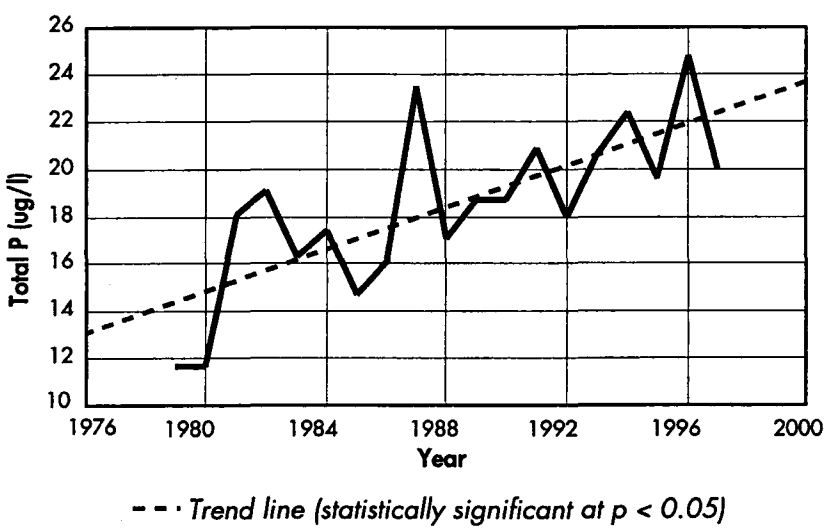

Figure 4. Total Phosphorus concentrations in Lake Sammamish 1979–1997.

Conclusions

The development and implementation of a watershed management plan for protecting the water quality in Lake Sammamish was, and is, dependent upon the active involvement of the citizens, businesses and governments that share the drainage basin. Due to the nonpoint nature of the pollutant of concern, phosphorus, there is no single solution that can prevent degradation of the lake's water quality. Instead, a wide range of structural and non-structural controls is needed. In recognition of the

fact that new technology and science may change the lake's management needs, the citizens and governments agreed to an adaptive management strategy. This strategy incorporates explicit review of the effectiveness of different management actions and land-use changes in the drainage basin. It allows for the introduction of new strategies, practices, or technologies into the management plan as needed.

The Plan recognizes that no one party is responsible for controlling the sources of phosphorus in the drainage basin. Rather, all activities that have the potential to generate phosphorus have been targeted. Structural controls, such as on-site water quality treatment facilities are being used for new development only since retrofitting of old urban development proved to be very expensive and unlikely to result in significant removal of phosphorus. The majority of phosphorus control is expected to be achieved through the conservation of forest and best management practices in the rural and forest production lands and through best management practices in the urban lands. Public funds support these practices through education and stewardship programs, technical assistance and compliance support programs and small grants.

The success of the Plan will be evaluated through time as part of the on-going adaptive management strategy and through the in-lake monitoring program.

Acknowledgments

Funding for the work described in this paper was provided by King County and the cities of Bellevue, Issaquah and Redmond. Additional support was provided by the Washington Department of Ecology. The authors would also like to thank the Lake Sammamish Technical and Management Committees, the Partners for a Clean Lake Sammamish, Dale Anderson, Brian Taylor, and Beth Schmoyer for their contributions to this work; and Laurel Preston, Wendy Gable and Jeff Richey for their assistance in manuscript preparation.

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[i] The management-tracking program will use an adaptive management strategy that allows incremental changes in management in response to experience, scientific finding and new technology.

Sources of Variability in Water Quality Monitoring Data

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Washington Department of Ecology

Abstract

The objective of many water quality monitoring programs is to detect changes in water quality (a trend) amidst the other sources of variability (noise) in the data. The ability to detect trends in water quality is directly related to the magnitude of the variability of the data. Sources of variability include: natural in-stream variability, variability due to sample collection and field processing, and variability due to laboratory analysis of the water. Using data from the Puget Sound Ambient Monitoring Program's Freshwater Monitoring Network (collected by the Department of Ecology) this paper estimates the variability of several variables due to these three sources and discusses the importance of each relative to trend analysis.

6A: Watersheds/Water Quality

Questions & Answers

Q: Mark and Joann, you were looking at bio-available phosphorus and you were talking about total phosphorus so what's the relationship? If both of you could comment on that.

Grey: Well, total phosphorus is just that, total. BAP, biological available phosphorus is dissolved phosphorus which arbitrarily is defined as that which can be measured that passes through a 45 micron filter. And the other portion of BAP is particulate phosphorus that is labile, or a common term is easily mineralized. So then total P minus BAP would be a more resistant phosphorus that is mineral in nature or a highly stable organic P molecule.

Richey: And just to add a little something to that, the reason that in management that we model using total phosphorus is that the database that we have for bioavailable phosphorus is extremely limited. What we've done is try to correlate total phosphorus concentrations in the lake to the lake conditions that we're looking to preserve. So we know that some part of the total phosphorus fraction is not available biologically.

Q: Mark, the City of Bremerton applies biosolids to forested lands and there are a couple of questions I have. The first is with permitting agencies for when you do apply biosolids to areas where there's potential to impact surface waters, it looks, from your study, that nitrate is really what we want to look for in biosolids application.

Grey: Certainly.

Fohn: Yes, that was a very good point. And also I just want to comment that you picked some incredibly heavy rain events that you sampled. I noticed the December 96 event and the March 97 event. So you've really hit some big ones.

Grey: Right. And because of limited time, I picked those out from more than 15 total rainfall events that I analyzed. I just pulled those for representation. I was looking at my notes, I didn't mention: ammonia is very soluble, and if you are applying any type of fertilizer, ammonia is a good indicator if you're having any water quality contamination. That differs from nitrate, especially in biosolids over the long term, because nitrogen has to go through the mineralization step to get to nitrate, so ammonia is a good indicator of that. And those were very, very heavy rainfall events where old water that was stored in the watershed mixes with new water. But, as I said, what I showed was that, even though there was some relationship to flow increasing ammonia concentrations, those were still below pre application levels.

Fohn: Did you see the nitrates come off during the lesser storm events?

Grey: Post application? Yes, certainly.

Fohn: And did you test for fecal coliform?

Grey: Yes, early on I did. Fecal coliform is difficult in rainfall events because the holding time for fecal coliform is six hours, so it's very difficult to sample for in terms of a large run off event. But, in that January event, there were, I think, six determinations and they were all, most of them, were no detects and some of them had like six fecal units per 100 milliliters. So very low. It's difficult for that, unless

you've got a direct conduit to the stream, I don't think you're going to see fecal run off from an application site.

Q: Joanna, you said you had some success for working with homeowners and other landowners on small lakes to reduce phosphorus loads. Could you outline what some of those efforts were and what actions they took?

Richey: The reason that I know this is the case is that we did the inevitable survey, We have small lake within the Lake Sammamish drainage basin called Beaver Lake. It's in the southeastern part of the drainage basin. Beaver Lake has a watershed that's totally, urban residential and it includes about 400 households. And it also is a phosphorus-limited lake and has a long history of management problems. We developed a nonpoint source management program for Beaver Lake a few years ago. That was done by Sharon Walton also at the King County Department of Natural Resources. And that lake, the people in that lake, voted to become a self-taxing district, or lake management district. And a major part of that management is to change their landscaping practices, to change the way they maintain their septic systems, to change to use of phosphorus in and around their gardens, their homes, their cars everything, pick up their pet waste, all the sources of phosphorus that come from residential development are being targeted by the lake management district. And they have done that essentially through a program, a multi-faceted program of education And, as you can imagine, before becoming a self-taxing district, a lot of education has to go on. so, they're not only changing their behavior, they are actually going to pay for the materials that are need to educated each other. What we did this past summer, and actually we're doing it again this summer, is we did a statistical survey asking people in the Beaver Lake management district and in the Lake Sammamish drainage many, many, many different questions about what they do in and around their homes, their daily activities, what their understanding of phosphorus pollution, lake limnology, nonpoint source control, etc. And interestingly enough, what we found is that the majority of residents in the Beaver Lake management district are extremely sophisticated and have actually changed their behavior in order to reduce the amount of phosphorus coming off their landscapes. We found that in the Lake Sammamish district most people had absolutely no idea what we were talking about. Seventy-five percent said, 'yes we know there is a pollution problem and we know it's caused by phosphorus.' However when we asked them specific questions bout what the activities that they did now and or activity changes they could make, they had absolutely no idea. That's given us a lot of information in terms of how education can really change people's behavior. That's why we're optimistic.

Q: Paul, it sounds like you may have made some assumptions about the source of the bacteria contaminants in the river. I'm wondering if you did any genetic work to see what those sources may have been or are?

Pickett: I didn't really make any assumptions about what the sources were. Initially with the study we just looked at where water was entering the river and sampling as many of those as we can. You can look at the land use and see what kind of land us exists in that basin and then, I guess in a sense, you might make some assumptions, at least about where to start looking.

We've looked into the genetic typing a little bit. There was the ribosomal RNA typing study in Pipers Creek and we've been talking to a researcher, whose name I can't think of at this moment. I don't think we really have a tool that's of practical use. The way I understand the current state of the art is that you can basically determine if a certain source is absent or present, so you can rule something out. But, if you find it, you don't know whether it's a tiny amount or most of it. There isn't a way to quantify it. That's my understanding of the current state of the art, although it would be nice to think that that could be improved because that could be a powerful tool.

PUGET SOUND RESEARCH '98

SESSION 6B

TOXIC EFFECTS

Session Chair:

John Armstrong
U.S. Environmental Protection Agency, Region 10

Exposure of Juvenile Chinook and Chum Salmon to Chemical Contaminants in the Hylebos Waterway of Commencement Bay

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Introduction

Estuaries are critical habitats for juveniles of several Pacific salmon species during their transition from fresh water to the ocean (Healy 1982). Estuarine habitats provide refuge from predators, a rich food supply to support rapid growth, and are where juvenile salmon make the adjustment from freshwater to marine conditions (Dorcey et al. 1978, Simenstad et al. 1982). Urban estuaries, however, receive inputs of toxic anthropogenic substances from a variety of sources, and many of these chemicals can accumulate in sediments (Dexter et al. 1985) and thus can be retained in the estuary. There is concern that, because juvenile salmon are undergoing numerous physiological adaptations during their residence in estuarine environments, any additional stresses, such as exposure to toxic chemicals, may be injurious.

The Hylebos Waterway located in Commencement Bay of Puget Sound is a contaminated estuary. Juvenile chinook and chum salmon inhabit this waterway in the late spring and early summer. During 1989 and 1990, juvenile chinook salmon were collected from three Commencement Bay waterways other than the Hylebos Waterway (Stein et al. 1995; Varanasi et al. 1993), and found to be substantially exposed to a variety of contaminants, including polycyclic aromatic hydrocarbons (PAHs) and chlorinated hydrocarbons (CHs). In addition, other studies from the Duwamish Waterway (Stein et al. 1995; Varanasi et al. 1993; McCain et al. 1990) showed levels of chemical contaminant exposure in juvenile chinook salmon similar to that found in the 1989 and 1990 studies of Commencement Bay. Juvenile chinook salmon from the Duwamish Waterway exhibit a variety of biological effects associated with their residence in this contaminated estuary, including reduced immunocompetence, increased mortality after disease challenge, and reduced growth (Varanasi et al. 1993; Arkoosh et al. 1991; Arkoosh et al. in press). Juvenile salmon from the Duwamish Waterway also have increased induction of hepatic cytochrome P4501A (CYP1A) and higher levels of DNA damage compared to juveniles from nonurban estuaries (Stein et al. 1995, Varanasi et al. 1993). Additionally, a recent laboratory investigation demonstrated that immunocompetence of juvenile chinook salmon can be impaired by exposure to CHs and PAHs (Arkoosh et al. 1994).

Prior to the current investigation, however, nothing was known about the potential for chum salmon to be exposed to chemical contaminants during residence in contaminated estuaries, or what the effects of increased exposure might have been on this species. Most importantly, there was no information on exposure of salmonids during residence in the Hylebos Waterway. Accordingly, the aim of the present investigation was to determine to what degree juvenile chum and chinook salmon from the Hylebos Waterway might be exposed to organic contaminants, and to compare the levels of exposure observed to previous studies where such exposures have been linked to biological dysfunction.

Methods

Sample Collection

Juvenile chum and chinook salmon were collected from the Hylebos Waterway, and from reference hatcheries and estuaries considered to be relatively unimpacted by contaminants (Varanasi

et al. 1993). Hylebos Waterway juvenile salmon were collected primarily within sight of the 11th Street Bridge, and fish were sampled weekly for six weeks in May and June, 1994. Fish were sampled once from each reference hatchery and estuary. Reference sites for chum salmon were the Puyallup Tribal Hatchery and the Skokomish Estuary. Reference sites for the chinook salmon were the Puyallup State Hatchery, the Nisqually Estuary, and the Nisqually Hatchery (however, no stomach contents were available for analyses from the Nisqually Hatchery). Beach seines were used to collect the juvenile salmon from the Hylebos Waterway and reference estuaries (PTI 1990; Varanasi et al. 1993). Fish captured from the Hylebos Waterway were held alive in aerated sea water until necropsies could be completed in the shipboard laboratory. Fish from hatcheries and reference estuaries were transported to the laboratory in aerated fresh water and sea water respectively, and held alive until necropsies could be completed.

Fish were weighed (g) and fork length was measured (mm). Bile, liver and stomach contents were collected as described in Varanasi et al. (1993), except that whole livers were collected and later subdivided for each type of analysis. Liver and stomach contents were composited into glass 20-mL vials previously rinsed with methylene chloride. Bile was composited into 4-mL vials containing glass limited-volume inserts. As soon as a composite was completed, it was immediately transferred to a freezer, or maintained on dry ice until it could be transferred to a freezer for storage. Liver samples were stored at –80 _C, and bile and stomach contents were stored at –20 _C until analyses were conducted.

We attempted to collect four composites/species at each site for every sampling period, however, the number of composites collected was dependent on the number of fish available. Each sample was a composite of tissue from 100–150 fish for chum salmon and 30–60 fish for chinook salmon. The number of fish included in a composite was dependent on the amount of tissue needed for analysis, size of the fish, and number of fish available.

Sampling in the Hylebos Waterway was ended when outmigrating salmon were no longer being captured in sufficient numbers to complete a composite for analysis. Due to the low numbers of composites collected at individual reference sites, data from analyses of fish collected at reference sites were combined prior to statistical analyses.

Sample Analysis

Fish liver was analyzed for a number of chlorinated hydrocarbons (CHs) using the methods described by Sloan et al. (1993). CHs most characteristic of the Hylebos Waterway are reported in this paper, and include HCB, HCBD, and sum of PCBs. Analyses were also done for toxic PCB congeners 105 and 118, sum of DDTs, chlordane, lindane, heptachlor, dieldrin and aldrin, but data for these analytes are not included in this paper. Stomach contents were analyzed for high and low molecular weight aromatic hydrocarbons as well the chlorinated hydrocarbons listed above, also using the methods of Sloan et al. (1993). Bile fluorescent aromatic compounds (FACs), including benzo[a]pyrene (BaP), phenanthrene (PHN) and naphthalene (NPH) equivalents, were analyzed by HPLC according to the methods of Krahn et al. (1986). Subsets of liver tissue were also analyzed for CYP1A activity (Collier et al. 1995) and for the presence of DNA adducts (Reichert and French, 1994).

Statistical Methods

Because environmental chemical concentrations and biomarker data are generally log-normally distributed, the data obtained from analyses of FACs in bile, CYP1A and DNA adducts in liver, and organic chemicals in liver and stomach contents were log-transformed prior to statistical analyses (Varanasi et al. 1995, Collier et al. 1986). Since zero values cannot be log-transformed, those values that were below detection limits were statistically analyzed by using 50% of the below detect value. This is a standard method of working with below detection limit values used by our laboratory and others (Bauer et al. 1992). Analysis of variance (ANOVA) was used to determine the statistical significance of differences between the combined data for fish collected during all sampling periods at the Hylebos Waterway and the combined data for reference fish.

Due to the low numbers of composites collected at individual reference sites, data from analyses of fish collected at reference sites were combined prior to statistical analyses. Scheffe's multiple comparison test showed no significant differences between the reference estuary and hatchery fish.

Results

Juvenile chum and chinook salmon captured in the Hylebos Waterway had significantly higher ($p<0.0001$) concentrations of hexachlorobenzene (HCB), hexachlorobutadiene (HCBD), and the sum of (Σ) polychlorinated biphenyls (PCBs) in their liver compared to juvenile salmon from reference estuaries and hatcheries (Tables 1 and 2).

Table 1. Concentrations of chlorinated hydrocarbons in juvenile chum salmon liver presented as mean concentration ±1 standard error (SE). N = number of samples analyzed. ANOVA was used to test for statistical differences between Hylebos Waterway fish and reference fish. Differences are considered statistically significant at *p* values ≤ 0.05 (in bold). Units of measure are ppb (ng/g) wet weight. * = some or all of the samples in this group had concentrations that were below detection limits; 50% of the below-detection value was used for statistical analyses. Reference sites are Puyallup Tribal hatchery and Skokomish estuary.

Analyte	Tissue	Mean conc. ± SE (N) for Hylebos	Mean conc. ± SE (N) for reference	*p* value
HCB	Liver	5.3 ± 0.4 (12)	0.52± 0.09 (6)	**$p < 0.0001$**
HCBD	Liver	2.5 ± 0.2 (12)	*0.08 ± 0.02 (6)	**$p < 0.0001$**
SPCBs	Liver	340 ± 20 (12)	40 ± 2.5 (6)	**$p < 0.0001$**

Table 2. Concentrations of chlorinated hydrocarbons in juvenile chinook salmon liver. Legend information and description of abbreviations and symbols is the same as for Table 1. Reference sites are Puyallup state hatchery, Nisqually hatchery, and Nisqually estuary.

Analyte	Tissue	Mean conc. ± SE (N) for Hylebos	Mean conc. ± SE (N) for reference	*p* value
HCB	Liver	2.3 ± 0.5 (8)	0.6 ± 0.1 (11)	**$p < 0.0001$**
HCBD	Liver	2.3 ± 0.8 (8)	*0.1 ± 0.06 (11)	**$p < 0.0001$**
SPCBs	Liver	130 ± 13 (8)	39 ± 5 (11)	**$p < 0.0001$**

Many of the chum and chinook juvenile salmon had little or no stomach contents, therefore, the amount of sample available for analyses allowed only one analysis per site for each of two reference sites, and two analyses for salmon from the Hylebos Waterway. Accordingly, only limited statistical analyses could be done with these few data points, and thus, for this study, the chemical analysis of stomach contents should be regarded as a qualitative indicator of contaminant exposure.

Concentrations of the sum of (Σ) high molecular weight aromatic compounds (HACs), HCBD, and ΣPCBs in stomach contents of juvenile chum salmon were significantly higher ($p< 0.05$) in Hylebos Waterway fish compared to reference fish (Table 3).

Table 3. Concentrations of aromatic and chlorinated hydrocarbons in juvenile chum salmon stomach contents. Legend information and description of abbreviations and symbols is the same as for Table 1. Reference sites are Puyallup Tribal hatchery and Skokomish estuary.

Analyte	Tissue	Mean conc. ± SE (N) for Hylebos	Mean conc. ± SE (N) for reference	*p* value
SLACs	Stom. Cont	540 ± 390 (2)	25 ±1 (2)	$p = 0.1$
SHACs	Stom. Cont	1300 ± 740 (2)	4.7 ± 1.1 (2)	**$p = 0.01$**
HCB	Stom. Cont	4.4 ± 1.1 (2)	0.7 ± 0.6 (2)	$p = 0.20$
HCBD	Stom. Cont	1.4 ± 0.4 (2)	*0.08 ± 0.03 (2)	**$p = 0.03$**
SPCBs	Stom. Cont	140 ± 10 (2)	41 ± 10 (2)	**$p = 0.04$**

Mean concentrations of HACs, and HCBD in stomach contents of chinook salmon were significantly higher ($p<0.05$) (Table 4) in fish captured from the Hylebos Waterway compared to fish from the reference areas (Nisqually River estuary and the Puyallup state hatchery). Although not statistically significant, mean concentrations of low molecular weight aromatic compounds (LACs) and HCB in stomach contents appeared higher in Hylebos fish compared to reference juvenile chinook salmon (Table 4).

Table 4. Concentrations of aromatic and chlorinated hydrocarbons in juvenile chinook salmon stomach contents. Legend information and description of abbreviations and symbols is the same as for Table 1. Reference sites are Puyallup state hatchery and Nisqually estuary.

Analyte	Tissue	Mean conc. ± SE (N) for Hylebos	Mean conc. ± SE (N) for reference	*p* value
SLACs	Stom. Cont	1200 ± 590 (2)	41 ± 32 (2)	***p* = 0.01**
SHACs	Stom. Cont	1800 ± 910 (2)	4 ± 1 (2)	***p* = 0.009**
HCB	Stom. Cont	2.8 ± 1.0 (2)	1.4 ± 1.1 (2)	*p* = 0.43
HCBD	Stom. Cont	1.0 ± 0.5 (2)	0.07 ± 0.01 (2)	***p* = 0.03**
SPCBs	Stom. Cont	92 ± 19 (2)	83 ± 57 (2)	*p* = 0.69

Concentrations of ΣPCBs in stomach contents of juvenile chinook salmon were not significantly different between the reference samples and the Hylebos Waterway samples. This is primarily because of the ΣPCB concentrations observed in stomach contents of chinook sampled from the hatchery. Although there were not enough samples for statistical analyses between the Hylebos Waterway and the Nisqually estuary fish, ΣPCBs in stomach contents of Hylebos Waterway chinook salmon were increased when compared only to chinook salmon from the Nisqually estuary.

Concentrations of metabolites of aromatic hydrocarbons in bile (biliary FACs) of chum salmon (Table 5) measured at benzo(a)pyrene wavelengths ($FACs_{BaP}$; a semi-quantitative estimate of metabolites of HACs), and phenanthrene and naphthalene wavelengths ($FACs_{PHN}$ and $FACs_{NPH}$ respectively; semi-quantitative estimates of metabolites of LACs), were all significantly higher ($p<0.0001$) in Hylebos Waterway fish compared to reference fish.

Table 5. Levels of biochemical indicators of contaminant exposure in juvenile chum salmon. Legend information and description of abbreviations and symbols is the same as for Table 1. Reference sites are Puyallup Tribal hatchery and Skokomish estuary. Units of measure are ng/g bile for bile analyses, pmol/mg/min for CYP1A, and nmol DNA adducts/mol DNA bases for DNA adducts.

Analyte	Tissue	Mean conc. ± SE (N) for Hylebos	Mean conc. ± SE (N) for reference	*p* value
FAC_{BaP}	bile	2200 ± 210 (16)	500 ± 78 (8)	***p* < 0.0001**
FAC_{NPH}	bile	310000 ± 26000 (16)	62000 ± 6900 (8)	***p* < 0.0001**
FAC_{PHN}	bile	78000 ± 7300 (16)	9500 ± 1300 (8)	***p* < 0.0001**
CYP1A	liver	88 ± 11 (12)	29 ± 4 (6)	***p* < 0.0001**
DNA adducts	liver	*8.1 ± 1.3 (12)	*2.7 ± 0.2 (5)	***p* = 0.008**

Concentrations of biliary FACs in juvenile chinook salmon (Table 6) measured at BaP, NPH, and PHN wavelengths were also statistically significant at $p<0.0001$ in Hylebos Waterway fish compared to reference fish.

Cytochrome P4501A (CYP1A), is a xenobiotic metabolizing enzyme inducible by a broad range of PAHs, CHs, and pesticides, and was measured as the activity of the CYP1A-dependent enzyme, aryl hydrocarbon hydroxylase (AHH). These activities were significantly higher ($p<0.0001$) in liver tissue of juvenile chum salmon from the Hylebos Waterway, compared to values for reference fish (Table 5). For chinook salmon, hepatic AHH activities were approximately 30% higher in fish from the Hylebos Waterway, compared to values for reference chinook (Table 6). This difference was statistically significant at $p=0.1$.

Concentrations of DNA adducts in liver, measured by the ^{32}P-postlabeling method, serve as a biological indicator of DNA damage due to exposure to, metabolism of, and covalent binding to DNA bases by PAHs. These adduct levels were about three times as high in juvenile chum salmon from the Hylebos compared to reference fish, and were statistically significant at p=0.008 (Table 5). However, juvenile chinook salmon showed no significant differences in levels of hepatic DNA adducts between fish captured from the Hylebos Waterway, compared to juvenile chinook captured from the reference sites (Table 6).

Table 6. Levels of biochemical indicators of chemical contaminant exposure in juvenile chinook salmon. Legend information and description of abbreviations and symbols is the same as for Table 1. Reference sites are Puyallup state hatchery, Nisqually hatchery and Nisqually estuary. Units of measure are ng/g bile for bile analyses, pmol/mg/min for CYP1A, and nmol DNA adducts/mol DNA bases for DNA adducts.

Analyte	Tissue	Mean conc. ± SE (N) for Hylebos	Mean conc. ± SE (N) for reference	*p* value
FAC_{BaP}	bile	2800 ± 490 (10)	1000 ± 100 (11)	***p* < 0.0001**
FAC_{NPH}	bile	520000 ± 86000 (10)	120000 ± 9100 (11)	***p* < 0.0001**
FAC_{PHN}	bile	110000 ± 19000 (10)	19000 ± 1900 (11)	***p* < 0.0001**
DNA add.	liver	*6.0 ± 1.1 (8)	*6.4 ± 0.7 (11)	*p* = 0.68
CYP1A	liver	97 ± 15 (8)	64 ± 13 (11)	*p* = 0.10

Discussion

Juvenile chum and chinook salmon from the Hylebos Waterway show an increased exposure to chemical contaminants, compared to fish from hatcheries or reference estuaries. The liver, stomach contents, and bile of both chum and chinook salmon from the Hylebos Waterway showed increased concentrations of aromatic compounds and their metabolites, and to HCB, HCBD, and ΣPCBs. Other chlorinated chemicals including toxic PCB congeners 105 and 118, ΣDDTs, hexachlor, lindane, dieldrin, aldrin, and chlordane, were also generally elevated in the liver of Hylebos Waterway juvenile salmon (Collier et al. 1998). There was also evidence of low to moderate contamination with chlorinated compounds in the feed used at the hatcheries, as shown by analyses of stomach contents (only one analysis per hatchery was conducted). However, it is apparent that any such contamination is not a major factor in the increased body burdens measured in fish from the Hylebos Waterway, because levels of PCBs and chlorinated pesticides in the liver were clearly elevated in fish captured from the Hylebos Waterway, compared to fish from either the hatcheries or other contaminated estuaries. The presence of high levels of HCBD in liver tissue and stomach contents provides strong evidence that exposure of these animals originates from the Hylebos Waterway, rather than from other waterways in Commencement Bay, because this compound is found in high levels in the sediments of the lower Hylebos Waterway (Collier et al. 1998; EVS, 1996; Malins et al. 1982), with dramatically lower levels found elsewhere in the Commencement Bay ecosystem (Malins et al. 1982; Krahn, pers. comm.). In fact, liver concentrations of HCBD in juvenile chum and chinook exceed those found in any previous studies of juvenile salmonids (Varanasi et al. 1993).

Associated with these increased concentrations of chemicals, there are indications of early biological alterations and damage, as shown by the increases in hepatic CYP1A-associated enzyme activity in both species and increased levels of DNA damage in chum salmon. Increases in both of these measures are well established as being linked to contaminant exposure (Collier and Varanasi 1991; Varanasi et al. 1992; Stein et al. 1992). However, the measurement of DNA damage is less sensitive than induction of CYP1A for determining comparatively short-term exposure to moderate levels of contaminants (Collier et al. 1988), which is likely the case for juvenile salmon inhabiting the Hylebos Waterway during their acclimation to marine conditions.

It is notable that chum salmon from the Hylebos Waterway generally showed higher indices of exposure than did chinook salmon. Whether this is due to increased exposure, decreased elimination, or other species-specific factors cannot be determined from the current data. Nonetheless, the apparent

higher contaminant concentrations in chum salmon raises the possibility that this species may be more susceptible to contaminant-induced biological injury than chinook salmon.

Concentrations of contaminants in juvenile chinook and chum salmon from the Hylebos Waterway are comparable to levels previously observed in juvenile chinook salmon from other industrial waterways (Figure 1). These contaminant concentrations have been shown to be associated with biological injury in juvenile chinook salmon. Contaminant concentrations similar to those measured in liver, stomach contents, and bile of juvenile salmon from the Hylebos Waterway are associated with impaired growth, suppression of immune function, and increased mortality following pathogen exposure in chinook salmon collected from another contaminated estuary in Puget Sound, the Duwamish Waterway (Varanasi et al. 1993; Arkoosh et al. 1991; Arkoosh et al. in press) For most measures in the current study, the concentrations of contaminants in Hylebos Waterway juvenile salmon are similar to, or in the case of HCBD, substantially higher than, concentrations measured in Duwamish Waterway fish (Figure 1).

As salmon complete smoltification and move from freshwater habitats to estuarine and marine habitats, they must adapt to a range of different pathogens and prey organisms, and are also subject to predation from different predators. Thus, impaired abilities to withstand pathogenic challenges and altered growth patterns should generally be considered to be deleterious with respect to early ocean survival of juvenile salmon utilizing contaminated habitats.

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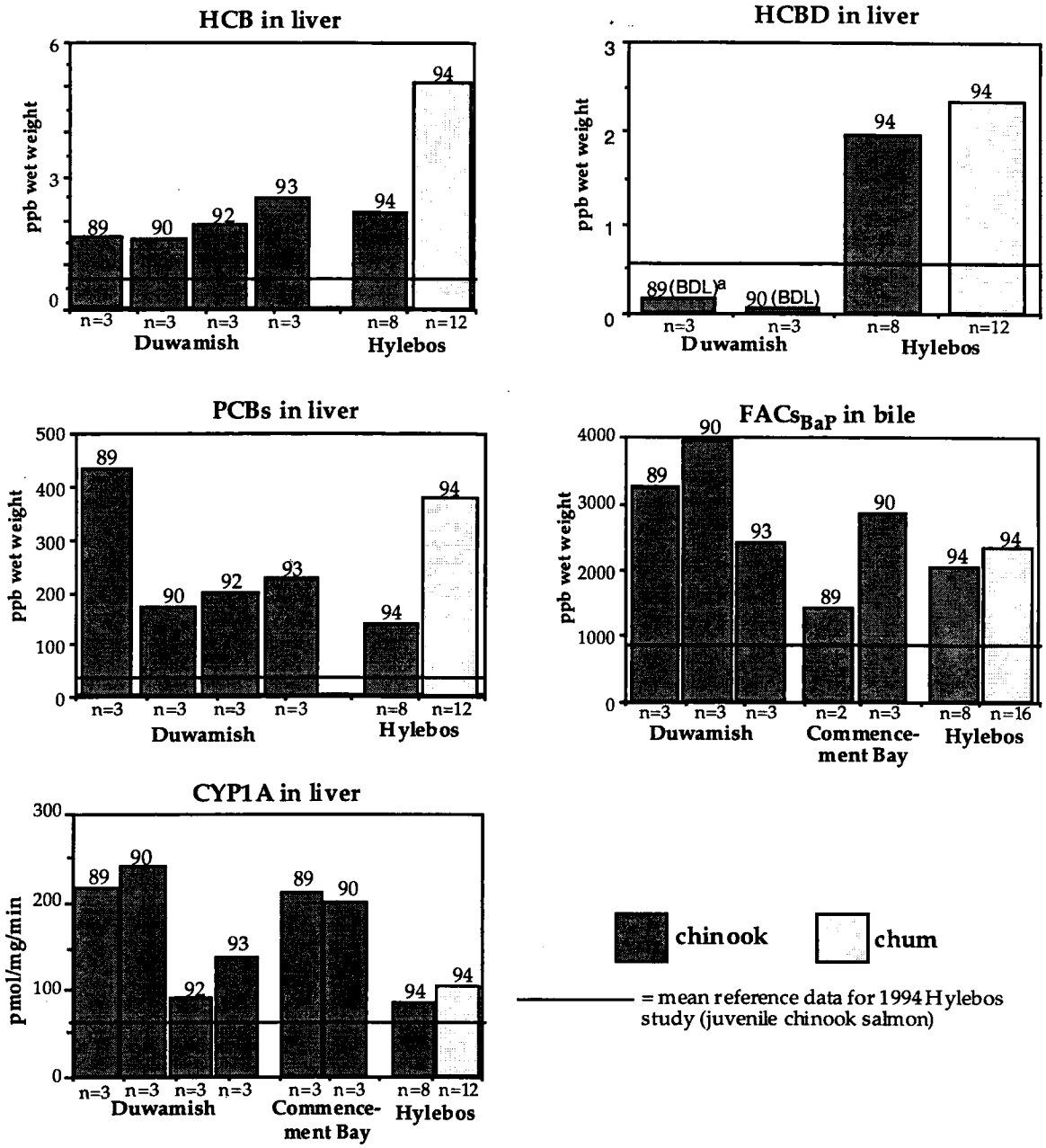

Figure 1. Comparisons of 1994 Hylebos Waterway juvenile salmon data with historical data from Puget Sound, WA. (Year of study is listed above each bar; the number [n] of composites analyzed at each site is listed below each bar.)

[a]BDL=all of the samples had concentrations that were below detection limits, therefore values were treated as if the concentration was 50% of the detection limit. (Sources: Duwamish and Commencement Bay 1989 and 1990 data from Stein et al. [1995] and Varanasi et al. [1993]. Duwamish 1992 and 1993 data from Casillas [unpublished data].)

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Toxicopathic Liver Pathology in Flatfish from the Hylebos Waterway in Tacoma, Washington

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Introduction

Histopathological examination is widely recognized as a useful, rapid method for assessing injury in marine fishes due to the adverse acute and chronic effects of exposure to anthropogenic contaminants (Moore and Myers, 1994). Certain pathological conditions (lesions) in the liver of wild fish—including neoplasms, preneoplastic foci of cellular alteration (FCA), proliferative lesions, and specific or unique degenerative/necrotic lesions (SDN)—are clearly involved in the histogenesis of hepatic neoplasia and morphologically resemble lesions induced by experimental exposure of rodents (Maronpot et al., 1986) and fish (Schiewe et al., 1991; Hawkins et al., 1990; Hendricks et al., 1984) to a variety of anthropogenic chemical toxicants including carcinogens. These toxicopathic lesions (having an etiology related to exposure to toxic chemicals) also have been shown statistically to be positively associated with exposure to xenobiotic chemical contaminants in numerous field studies in various fish species (reviewed in Moore and Myers, 1994). Moreover, certain hepatic lesions in English sole have been associated with changes in serum chemistry parameters indicative of liver dysfunction (Casillas et al., 1985).

In the many studies done on English sole from Puget Sound and other sites on the Pacific Coast, the chemicals consistently found to most strongly influence the probability of occurrence of these liver lesions are polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and DDT and its derivatives. The one consistently significant biological risk factor for liver lesion occurrence in these studies is fish age, with risk of being affected by neoplasms and preneoplastic FCA rising incrementally with each year of age (Rhodes et al., 1987; Myers et al., 1991, 1994; O'Neill, this volume). Moreover, certain early biochemical responses to contaminant exposure (biomarkers) have been statistically associated with increased risk of toxicopathic liver lesion occurrence. These biomarkers include levels of metabolic conversion products of PAHs detectable as fluorescent aromatic compounds (FACs) in bile (Krahn et al., 1986; Myers et al., 1991, 1994, 1998); hepatic activities of the xenobiotic metabolizing enzyme cytochrome P4501A (CYP1A) inducible by PAHs and chlorinated hydrocarbons (CHs) (Myers et al., 1998; Collier and Varanasi, 1991), and hepatic levels of hydrophobic DNA adducts representing reactive intermediates of PAHs covalently bound to DNA bases (Myers et al., 1998; Stein et al., 1993). This DNA damage by carcinogens and subsequent generation of mutations is a necessary early step in the process of initiation of neoplasia (Stein et al., 1993). Therefore, certain liver lesions have clear utility as biomarkers of contaminant exposure and effects, and have become useful as indicators of environmental degradation in marine ecosystems.

English sole and rock sole are both relatively territorial benthic species that occupy their feeding grounds for the majority of the year, exhibit some degree of homing ability, and display only limited seasonal migrations related to reproductive activities (Day, 1976; Forrester, 1969; Holland, 1969). Therefore, they are useful sentinel species in studies assessing potential effects of chemical contaminants. Among the many field studies done on these species that have focused on histopathological examination and documentation of chemical exposure, several studies done in the late 1970s and early 1980s showed relatively high prevalences of toxicopathic hepatic lesions at multiple sites within Commencement Bay, including sites in the Hylebos Waterway (Malins et al., 1984; Becker et al., 1987). The data from these earlier studies, in part, formed the basis for the designation of Commencement Bay and several of its

waterways, including the Hylebos Waterway, as priority Superfund sites in 1981. The existence of this historical data affords a unique opportunity to test the hypothesis that shore-based cleanup activities and natural remediation processes in the Hylebos Waterway have significantly altered the prevalences of liver lesions known to be strongly associated with chronic exposure to chemical contaminants.

These previous studies were used as the basis for the present work. Although rock sole were sampled in the larger damage assessment study and show results similar to English sole (Collier et al., 1998), in the interest of brevity only the data for English sole will be presented here. The major objectives of this study were to (1) assess the extent of exposure to various chemical contaminants, and the magnitude of various early biochemical responses to this exposure (biliary FACs, hepatic CYP1A and hydrophobic DNA adducts) in English sole captured from sites in the Hylebos Waterway and a relatively uncontaminated reference site at Colvos Passage; (2) determine the prevalence of toxicopathic liver lesions in English sole from these same sites; (3) determine the relationships, if any, among various indices of chemical contaminant exposure and early responses to this exposure, and hepatic lesion occurrence in this species by various statistical methods; and (4) compare lesion prevalences and the magnitudes of early biochemical responses to contaminant exposure detected in the present study to available historical data from the Hylebos Waterway.

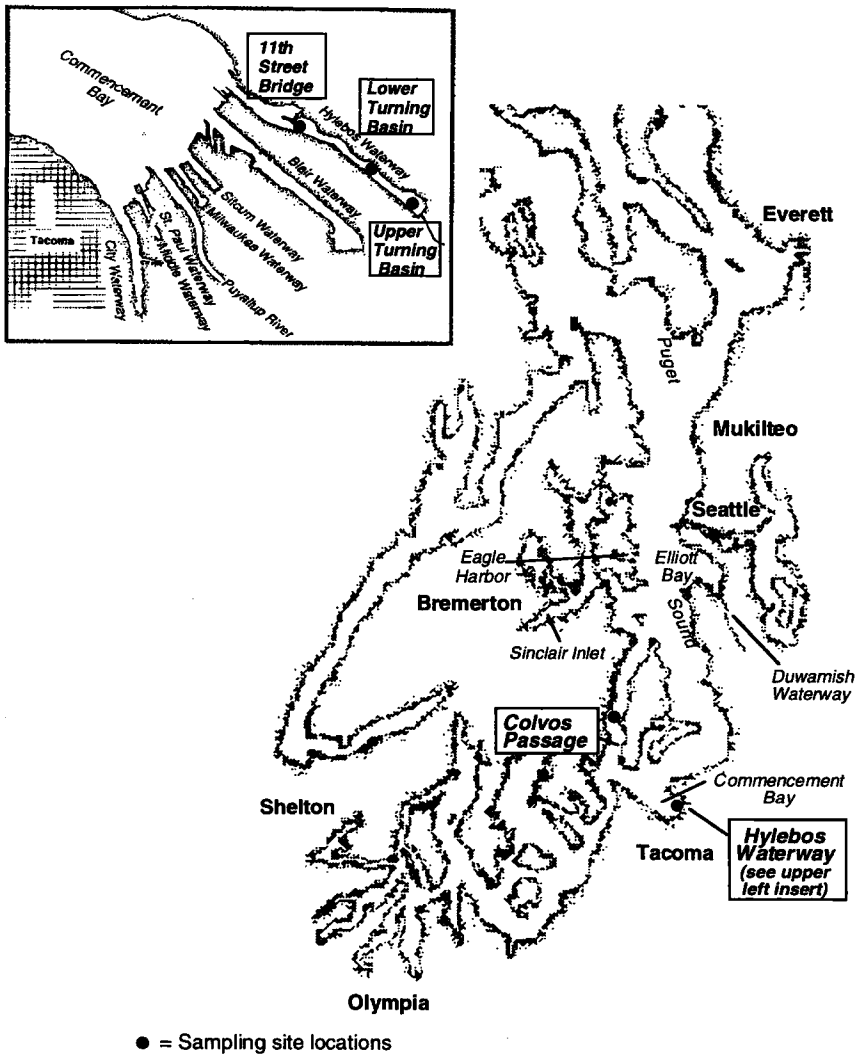

Figure 1. Sampling sites for flatfish toxicopathic injury study for the Hylebos Waterway.

Methods

Sample Collection and Analysis

Adult English sole were collected by otter trawl from sites in the Hylebos Waterway and a reference site in Colvos Passage (Figure 1), following standardized methods described in detail in Collier et al. (1998). Sampling was conducted in the Hylebos in July of 1994 and in Colvos Passage in September and October of 1994. Approximately 60 English sole at each site were collected from the Upper Turning Basin, lower Turning Basin, and 11th St. Bridge sites in the Hylebos Waterway, and from the Colvos Passage site. Otoliths were collected for age determination, and liver, kidney, and ovary were collected for histopathological examination; (data on kidney and ovarian lesions and other indicators of reproductive dysfunction are discussed in Collier et al. [1998] and Johnson et al. [this volume]). Liver, bile, and stomach contents were collected for measurement of chemical contaminant levels, and separate portions of liver from individual fish were also collected for measurement of CYP1A activity and DNA damage.

Methods for chemical and biological analyses (i.e., fish age determination, chemical analyses of liver tissue and stomach contents, measurement of biomarkers in bile and liver, and histopathological examination of fish tissues) are described in detail in Collier et al. (1998). Biliary FAC concentrations reported here and used in various correlative statistical analyses were adjusted for protein content of the bile sample, which corrects for variations in bile metabolite levels related to the feeding status of the sampled fish (Collier and Varanasi, 1991).

Statistical Methods

Details of statistical analyses performed are found in Collier et al. (1998). Briefly, analyses were performed: (1) to evaluate relationships among indices of contaminant exposure, early biochemical responses to exposure, and liver lesion occurrence; and (2) to compare data from English sole captured among three unique sites in the Hylebos Waterway, and the Hylebos Waterway as a whole, with data from the same species collected from the Colvos Passage reference site. Analysis of variance (ANOVA) (Zar, 1984) was used to identify significant intersite differences in chemical concentrations in liver and stomach contents, biliary FACs, and hepatic CYP1A and DNA adducts. Stepwise logistic regression (Breslow and Day, 1980) was used to identify significant relationships between potential risk factors and lesion occurrence. Two types of logistic regression analyses were conducted: (1) those examining the relative risk of disease, as estimated by the calculated odds ratio in individual fish, in relation to the variables of site of capture, age, biliary FACs levels, and hepatic DNA damage as adduct concentrations; and (2) analyses to assess the significance of the relationships between prevalences of lesions at the sampling sites and discrete risk factors, including levels of contaminants in liver and stomach contents, mean biliary FACs concentrations, mean CYP1A activities, and mean hepatic DNA adducts, while adjusting for mean fish age. In the latter analysis each sampling point for a species at a site was treated as an independent occurrence. These multivariate analyses permitted evaluation of contaminant-exposure/lesion-occurrence relationships, while simultaneously adjusting for fish age, a variable well known for its influence on risk of hepatic lesion occurrence (Rhodes et al., 1987; Myers et al., 1991, 1994, 1998; Moore and Myers, 1994; O'Neill et al., this volume).

For the first set of regression analyses above, odds ratios for particular lesion categories at a site were calculated and interpreted relative to the lesion occurrence at the Colvos Passage reference site. Increased probabilities of lesion occurrence were indicated by odds ratios greater than 1.000. Calculated odds ratios for age (in years) were interpreted for each additional year of age. For the second set of analyses, separate analyses were performed for each contaminant, contaminant class, biomarker of early response or risk factor discussed above, with results expressed as the significance of the association (p value). Because many of the contaminant exposure-related risk factors assessed in this analysis are known to be highly intercorrelated (Myers et al., 1994), it was not mathematically possible to include all risk factors into a

single multivariate analysis. Consequently, relationships between chemicals and chemical response risk factors and lesion prevalences were evaluated separately, while adjusting for potential effects of mean fish age at the sampling sites.

The contaminants, contaminant classes, and biomarkers of early response to contaminant exposure evaluated as risk factors for hepatic lesions were: high molecular weight aromatic compounds (HACs) and low molecular weight aromatic compounds (LACs) in stomach contents; PCBs, congener PCB 105, congener PCB 118, DDTs, hexachlorobenzene (HCB), hexachlorobutadiene (HCBD), chlordanes ($\alpha + \Gamma$), aldrin, dieldrin, heptachlor, and lindane in stomach contents and liver tissue; biliary FACs measured at benzo(a)pyrene wavelengths ($FACs_{BaP}$), at naphthalene wavelengths ($FACs_{NPH}$), and at phenanthrene wavelengths ($FACs_{PHN}$); and hepatic CYP1A and DNA adducts. A detailed description of these contaminants and classes is contained in Collier et al. (1998). These contaminants were measured and selected for analyses relating contaminant exposure to disease risk because they are found at high levels in sediments or fish from sites in embayments and estuaries located near major metropolitan centers (Myers et al., 1994), and because they represent broad classes of chemicals with documented toxic and/or carcinogenic potential in vertebrates (Klaasen et al., 1986) including fish (Meyers and Hendricks, 1982). The biomarkers of early response to contaminants were chosen because of their well known sensitivity to PAH exposure (biliary FACs, hepatic CYP1A, hepatic DNA adducts) and CH and pesticide exposure (CYP1A) in fish (Collier and Varanasi, 1991; Stein et al., 1993, 1994; Payne et al., 1987).

Pertinent data from male and female English sole form the "reproductive injury" portion of the broader damage assessment study and were incorporated into various statistical analyses in the present study; please refer to Collier et al. (1998) for information on sampling dates, number of English sole collected, and other relevant information.

Major Findings and Discussion

Objective 1: Determine Levels of Chemical Exposure in English Sole from the Hylebos Waterway

Adult English sole living in the Hylebos Waterway are clearly exposed to low and high molecular weight PAHs, PCBs, DDTs, HCB, and HCBD, regardless of whether the exposure is assessed by analyzing stomach contents (Figures 2–3), PAH metabolites in bile (Figure 4) or PCBs in liver (Figure 8) as an example of other CHs. Concentrations of these contaminants were generally 1–2 orders of magnitude higher in stomach contents of sole from Hylebos sites as compared to Colvos Passage reference fish. Among indices of exposure to PAHs, dietary exposure (stomach content LACs and HACs, Figure 2) was up to two orders of magnitude higher in sole from the Hylebos sites, and biliary FACs were 4–10 times higher at the Hylebos sites, with a clear pattern of increasing PAH exposure by both indices in sole from the sites further up the waterway (Figure 4). As a molecular dosimeter of exposure to genotoxic PAHs (Stein et al., 1992, 1994), DNA adduct levels in liver were also significantly higher in sole from Hylebos sites, showing progressively increasing levels in fish from sites further up the waterway (Figure 6).

Levels of dietary exposure to and hepatic bioaccumulation of PCBs (Figures 3, 5) and DDTs (data shown in Collier et al., 1998) were 15–25 times higher in sole from Hylebos sites compared to Colvos Passage reference fish, and like the PAHs, also showed a clear pattern of increasing exposure in English sole from the upper two sampling sites in the Hylebos Waterway. Exposure to HCB and HCBD, chemicals that are markers for the complex mixture of CHs in Hylebos Waterway sediments, was most pronounced in sole from the 11th St. Bridge site (data shown in Collier et al., 1998).

Levels of hepatic CYP1A induction, a biochemical response to organic contaminants such as PAHs and CHs, were significantly higher for English sole living in the Hylebos Waterway than those from the Colvos Passage reference site, regardless of where in the waterway they were captured (Figure 6).

Overall, there was a high degree of consistency for all exposure indices measured (except those for HCB and HCBD, and CYP1A in liver), demonstrating increased exposure and biochemical response to exposure moving from the near the mouth to the head of the Hylebos Waterway. Although the data for rock sole are not discussed specifically in this paper, it is important to note this consistency was also evident in the close similarity in exposure levels among rock and English soles from the single common sampling site in the Hylebos (11th St. Bridge). The marked differences in many exposure parameters for fish captured among the three sites sampled in the Hylebos Waterway, the consistency among different measures of exposure to the same chemical class, and site-specific parallels in exposure data between the two target species (see Collier et al., 1998 for rock sole exposure data) clearly show that exposure closely reflects the site of capture within the Hylebos Waterway. These data lead us to conclude that there is fidelity in feeding areas and limited movement of fish among the Hylebos sites.

Objective 2: Determine Prevalences of Toxicopathic Liver Lesions in English Sole from the Hylebos Waterway

We found significantly increased relative risks for occurrence of several liver lesion categories that were associated with residence at sites within the Hylebos Waterway, while accounting for the important variable of fish age (Figures 7–8). Although low prevalences of certain lesion categories occurred in both species at the reference site, this is not a unique finding based on previous studies on these species in Puget Sound (Malins et al., 1984; Myers et al., 1991, 1994; Krahn et al., 1986; Becker et al., 1987; O'Neill et al., this volume). Significantly increased relative risks were shown for several lesion categories in English sole from sites in the Hylebos Waterway, relative to Colvos Passage (Figure 7). Estimated relative risks of 2.7–74 times that for comparably aged English sole from Colvos Passage were determined for SDN, proliferative lesions, and "any toxicopathic liver lesion," for example, at the three separate Hylebos sites. Relative risks for SDN were significantly and consistently higher at all three sites, with progressively higher relative risks as one moved up the waterway. In analyses combining all data from both the toxicopathic injury and reproductive injury studies (Figure 8), increased relative risks were shown for these same lesion categories, at values up to 26 times the baseline risk at Colvos Passage.

In prior studies of English sole from Puget Sound using this same statistical method, relative risks for hepatic lesion occurrence ranged from 2.7 (SDN, South Seattle Waterfront) to 8.7 (neoplasms, Upper Duwamish Waterway) when fish from Port Madison were used as the reference population (Rhodes et al., 1987). In studies incorporating data from the Puget Sound Ambient Monitoring Program (PSAMP, 1989–1993) and using a much larger database from multiple reference sites to establish a baseline (Myers et al., 1995), significantly increased estimated relative risks (RR_e) of lesion occurrence at a sampling site in Commencement Bay were shown for neoplasms (RR_e = 7.7), FCA (RR_e = 7.7) and SDN (RR_e = 11). Similar estimated relative risks occurred at the Elliott Bay site (range 2–20), and much higher ones (range 31–71) at the Duwamish Waterway site. If the lesion occurrence and age data in Hylebos English sole from the present study were to be analyzed and compared to the reference site data from either of these prior studies (where lesion prevalences were much lower than those shown in Colvos Passage English sole), it is highly probable that the estimated relative risks of lesion occurrence in English sole from the Hylebos sites in the present study would have approached or exceeded those shown for the Commencement Bay and Elliott Bay sites in that prior study. For example, prevalences in English sole from Commencement Bay in that study were ~5% for SDN, 12% for FCA, and 5% for neoplasms, and in Elliott Bay English sole were 10% for SDN, 11% for FCA, and 5% for neoplasms. Prevalences of the same lesion categories in English sole from the Hylebos sites in the current study were similar, and in some cases higher.

Objective 3: Determine Risk Factors Associated with Liver Lesion Occurrence in English Sole from the Hylebos Waterway

The results of logistic regression analyses assessing potential relationships between contaminant exposure and injury in the form of toxicopathic liver lesions (see Collier et al., 1998 for detailed data)

were quite similar to those previously conducted on English sole (Myers et al., 1991, 1994, 1995; Rhodes et al., 1987; O'Neill et al., this volume). Exposure to PAHs, PCBs (including mono-ortho substituted toxic coplanar congeners PCB 105 and PCB 118), and DDTs were the risk factors most commonly associated with hepatic lesion occurrence (see Collier et al., 1998 for details). However, as in those previous studies, because of the covariance of these contaminants it is not possible to quantify the proportional risk attributable to each of these chemical classes. Nonetheless, PAHs are toxicologically meaningful risk factors because of the experimentally demonstrated hepatotoxicity and carcinogenicity of these compounds and their prominent role as genotoxicants in the initiation of carcinogenesis. In contrast, the mode of action for PCBs and DDTs appears to be as nongenotoxic promoters of carcinogenesis by virtue of their cytotoxicity and subsequent stimulation of cell proliferation (reviewed in Myers et al., 1987, 1994; Moore and Myers, 1994). In addition, experimental exposures of fish to these CHs have resulted in the formation of liver lesions identical to those included in the SDN category, including megalocytic hepatosis and nuclear pleomorphism (reviewed in Myers et al., 1987, 1994; Moore and Myers, 1994). Neither HCB nor HCBD were strong risk factors for toxicopathic hepatic lesions in English sole in the current study, primarily because levels of dietary exposure and hepatic bioaccumulation of these compounds were comparatively low (relative to those at the 11th St. Bridge site) at other sites in the Hylebos displaying higher lesion prevalences.

Results of logistic regression analyses relating mean hepatic CYP1A activity levels to lesion prevalences for English sole also showed CYP1A induction as a significant risk factor for the most common hepatic lesion, SDN (see Collier et al., 1998 for detailed data). These results are consistent with other studies in English sole from Puget Sound, and the role of CYP1A in the metabolism and bioactivation of PAHs to their genotoxic and cytotoxic intermediates, as well as its inducibility by and metabolism of CHs (Collier and Varanasi, 1991).

Finally, lesion prevalences in English sole from Hylebos Waterway sites generally paralleled levels of DNA adducts in liver from the same fish and same sites. Highest mean levels of adducts were in English sole at the Upper Turning Basin site where hepatic lesion prevalences were also highest. Also, in logistic regression analyses examining the increased risk of lesion occurrence attributable to hepatic DNA damage, adduct levels were significant risk factors for FCA, SDN and "any toxicopathic hepatic lesion" (see Collier et al., 1998 for detailed data). These results parallel those of prior studies (Myers et al., 1995b, 1998) and provide further evidence linking measures of PAC exposure to hepatic lesion occurrence in benthic fish, especially for lesions occurring early in the histogenesis of hepatic neoplasia such as SDN and FCA (Myers et al., 1987; Moore and Myers, 1994). Levels of DNA adducts in livers of Hylebos Waterway English sole from the current study were similar to those determined by comparable quantitation methods in sole from Eagle Harbor in Puget Sound prior to capping of PAH-contaminated sediments (Myers et al., 1995b; Collier and Myers, 1997), and those estimated from previous 1988 data (Stein et al., 1992) in sole from the Duwamish Waterway. Both of these sites are also highly contaminated (primarily with PACs and/or PCBs) urban sites in Puget Sound exhibiting high prevalences of liver lesions in resident flatfish species.

Objective 4: Determine whether Appreciable Changes in Liver Lesion Prevalence and Values for Biochemical Measures of Early Response to Contaminant Exposure Have Occurred Since the Late 1970s

Drawing from the several studies done on English sole between 1979 and 1985, there is neither a substantial decrease in injury as overall toxicopathic liver lesion prevalence at the specific Hylebos sites, nor in the Hylebos Waterway as a whole (Figure 9). More importantly, prevalences of most of the liver lesions in English sole from the Hylebos Waterway continue to far exceed those found in sole from relatively uncontaminated reference sites in Puget Sound. Current concentrations of biliary $FACs_{BaP}$ in English sole are well within the range of values determined in 1987–88 (Figure 10), and in the case of the Upper Turning Basin, are much higher than historical values. Similarly, the mean DNA adduct levels and CYP1A activities in liver found in the current fish injury study are

within or exceed the mean values determined in 1987–88 (Figures 11 and 12).

Overall, the data do not provide evidence that natural or engineered remediation processes over the last 10–15 years have resulted in a substantial improvement in the extent of chemical exposure and associated liver injury to English sole in the Hylebos Waterway.

Figures

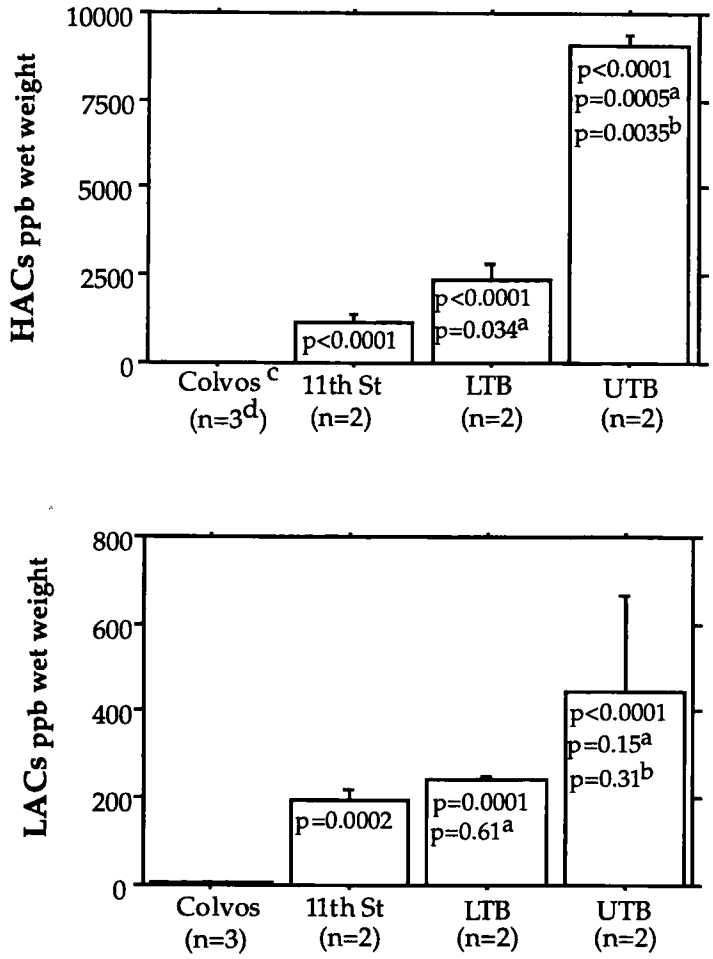

Figure 2. Concentrations of aromatic hydrocarbons in stomach contents of English sole from the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington. Values are mean concentrations ± one standard error (SE). The *p* (or probability) value shown is for the statistical comparison between Hylebos Waterway sites and the Colvos Passage reference site, unless otherwise noted. Mean concentrations and statistical comparisons are derived from an analysis of variance (ANOVA).

[a]*p* value for the upper Turning Basin or lower Turning Basin compared to the 11th Street Bridge site.

[b]*p* value for the comparison between the upper Turning Basin and lower Turning Basin sites.

[c]abbreviations: Colvos = Colvos Passage; 11th St = 11th Street Bridge site in Hylebos Waterway; LTB = lower Turning Basin site in Hylebos Waterway; UTB = upper Turning Basin site in Hylebos Waterway; HACs = high molecular weight aromatic compounds; LACs = low molecular weight aromatic compounds. Analytes included in HACs and LACs are listed in Appendix 2 of Collier et al. (1998).

[d]the number of analyses conducted (n) is indicated beneath each site name.

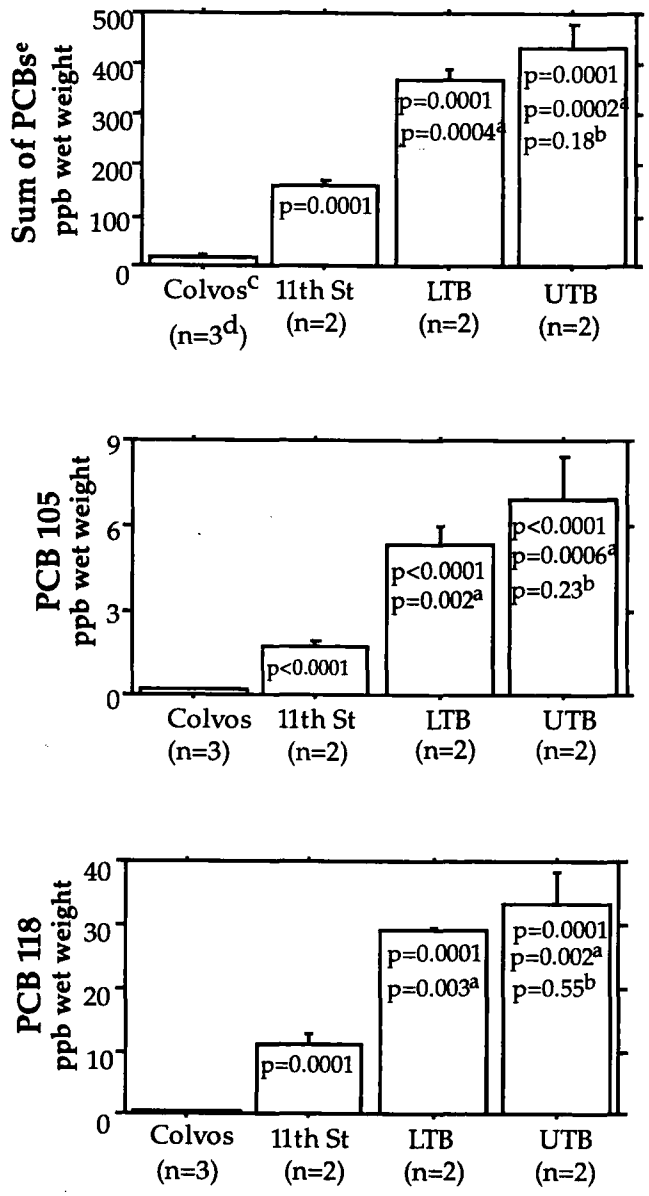

Figure 3. Polychlorinated biphenyls (PCBs) in English sole stomach contents sampled from the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington. Values are mean concentrations ±SE. The *p* value shown is for the statistical comparison between Hylebos Waterway sites and the Colvos Passage reference site, unless otherwise noted.

[a]*p* value for the UTB or LTB compared to the 11th Street Bridge site.

[b]*p* value for the comparison between the UTB and LTB sites.

[c]site abbreviations: Colvos = Colvos Passage; 11th St = 11th Street Bridge site in Hylebos Waterway; LTB = lower Turning Basin site in Hylebos Waterway; UTB = upper Turning Basin site in Hylebos Waterway.

[d]the number of analyses conducted is indicated beneath each site name.

[e]analytes included in the sum of PCBs are listed in Collier et al. (1998).

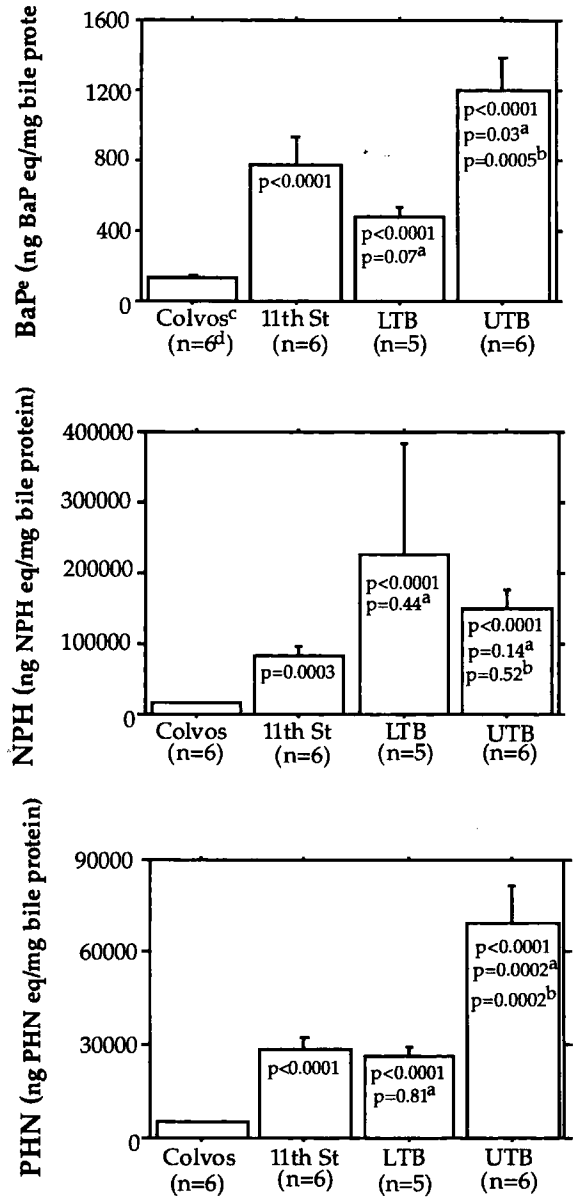

Figure 4. Concentrations of fluorescent aromatic compounds (FACs) in bile of English sole from the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington. Values are mean concentrations +SE. The *p* value shown is for the statistical comparison between Hylebos Waterway sites and the Colvos Passage reference site, unless otherwise noted.

[a]*p* value for the UTB or LTB compared to the 11th Street Bridge site.

[b]*p* value for the comparison between the UTB and LTB sites.

[c]site abbreviations: Colvos = Colvos Passage; 11th St = 11th Street Bridge site in Hylebos Waterway; LTB = lower Turning Basin site in Hylebos Waterway; UTB = upper Turning Basin site in Hylebos Waterway.

[d]the number of analyses conducted is indicated beneath each site name.

[e]BaP = mean values for benzo[a]pyrene wavelength equivalents (sum of high molecular weight FACs); NPH =mean values for naphthalene wavelength equivalents (sum of low molecular weight FACs); PHN = mean values for phenanthrene wavelength equivalents (sum of mid-level molecular weight FACs). Biliary FACs have been adjusted for protein concentration.

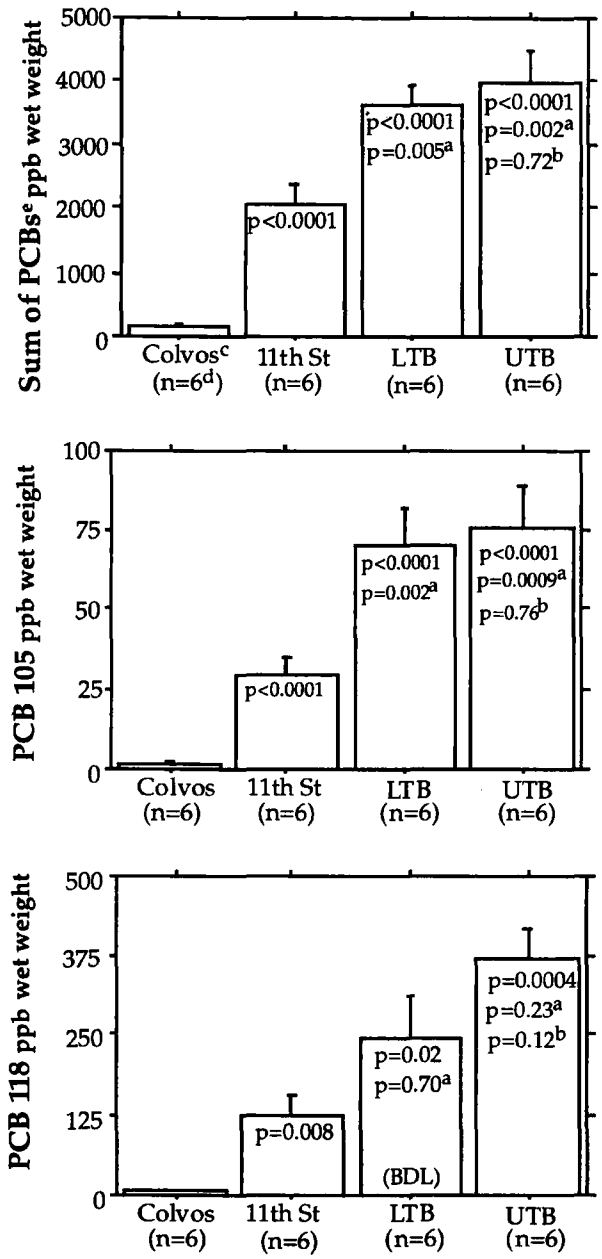

Figure 5. Polychlorinated biphenyls (PCBs) in English sole liver from the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington. Values are mean concentrations ±SE. The *p* value shown is for the statistical comparison between Hylebos Waterway sites and the Colvos Passage reference site, unless otherwise noted.

[a]*p* value for the UTB or LTB compared to the 11th Street Bridge site.

[b]*p* value for the comparison between the UTB and LTB sites.

[c]site abbreviations: Colvos = Colvos Passage; 11th St = 11th Street Bridge site in Hylebos Waterway; LTB = lower Turning Basin site in Hylebos Waterway; UTB = upper Turning Basin site in Hylebos Waterway.

[d]the number of analyses conducted is indicated beneath each site name.

[e]analytes included in the sum of PCBs are listed in Collier et al. (1998).

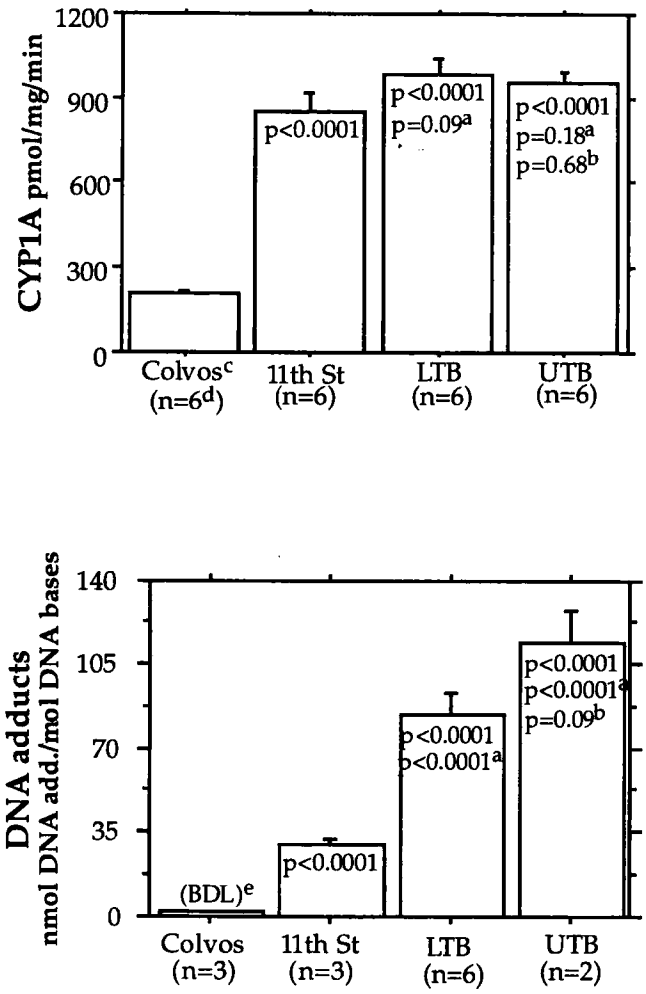

Figure 6. Cytochrome p4501A and DNA adducts in English sole liver from the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington. Values are mean concentrations ±SE. The *p* value shown is for the statistical comparison between Hylebos Waterway sites and the Colvos Passage reference site, unless otherwise noted.

[a]*p* value for the UTB or LTB compared to the 11th Street Bridge site.

[b]*p* value for the comparison between the UTB and LTB sites.

[c]site abbreviations: Colvos = Colvos Passage; 11th St = 11th Street Bridge site in Hylebos Waterway; ITB = lower Turning Basin site in Hylebos Waterway; UTB = upper Turning Basin site in Hylebos Waterway.

[d]the number of analyses conducted is indicated beneath each site name.

[e]BDL = some or all of the samples in this group had concentrations that were below detection limits. Detection limits vary depending on the sample size; detection limits for specific samples are listed in the case narrative. Samples with values below detection limits were treated as if the concentration was 50% of the detection limit.

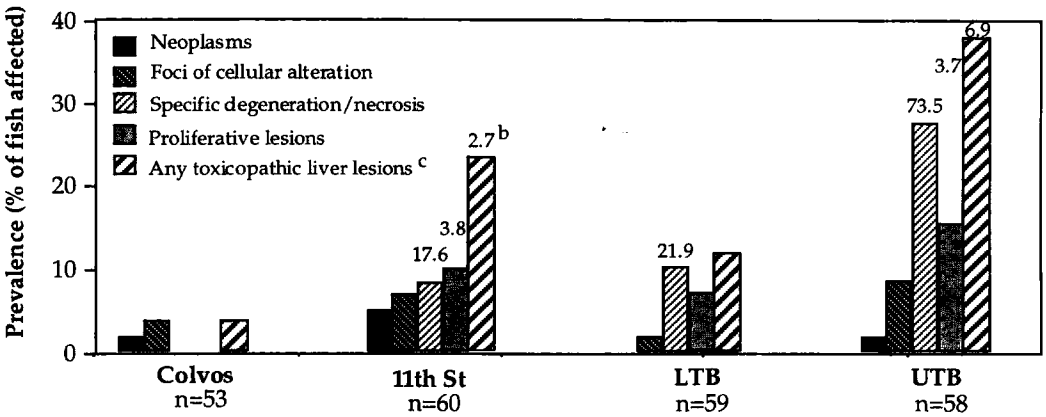

Figure 7. Prevalences of toxicopathic hepatic lesions in English sole from unique sites in the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington.

[a]site abbreviations: Colvos = Colvos Passage (reference site); 11th St = 11th Street Bridge site in Hylebos Waterway; LTB = lower Turning Basin site in Hylebos Waterway; UTB = upper Turning Basin in Hylebos Waterway.

[b] numbers above lesion bars indicate the significantly higher ($p<0.05$) estimated relative risks for that lesion category, as compared to fish from Colvos Passage (data combined from both studies, n = 195), by logistic regression while accounting for effects of fish age on probability of lesion occurrence.

[c]the "any toxicopathic liver lesion" category includes fish having one or more toxicopathic lesion types including: neoplasms, foci of cellular alteration, specific degenerative/necrotic lesions, and proliferative lesions.

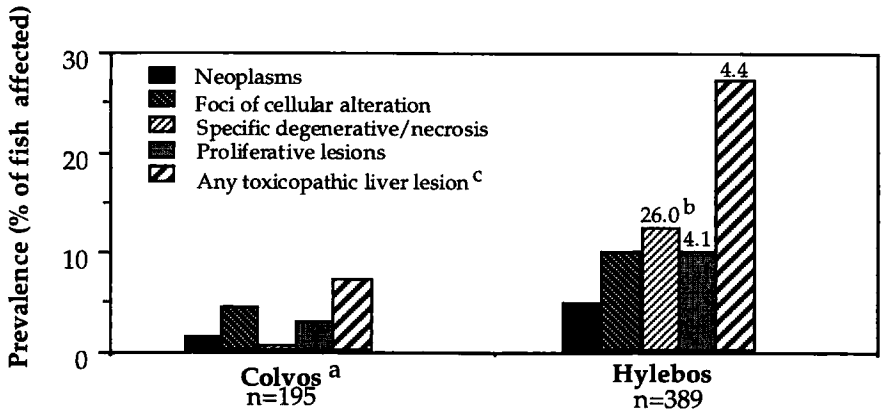

Figure 8. Prevalences of toxicopathic hepatic lesions in male and female English sole sampled during the combined toxicopathic injury and reproductive injury portions of the 1994–95 fish injury studies of the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington.

[a]site abbreviations: Colvos = Colvos Passage (reference site); Hylebos = Hylebos Waterway.

[b]numbers above lesion bars indicate the significantly higher ($p<0.05$) estimated relative risks for that lesion category, as compared to fish from Colvos Passage (data combined from both studies, n = 195), by logistic regression while accounting for effects of fish age on probability of lesion occurrence.

[c]the "any toxicopathic liver lesion" category includes fish having one or more toxicopathic lesion types including neoplasms, foci of cellular alteration, specific degenerative/necrotic lesions, and proliferative lesions.

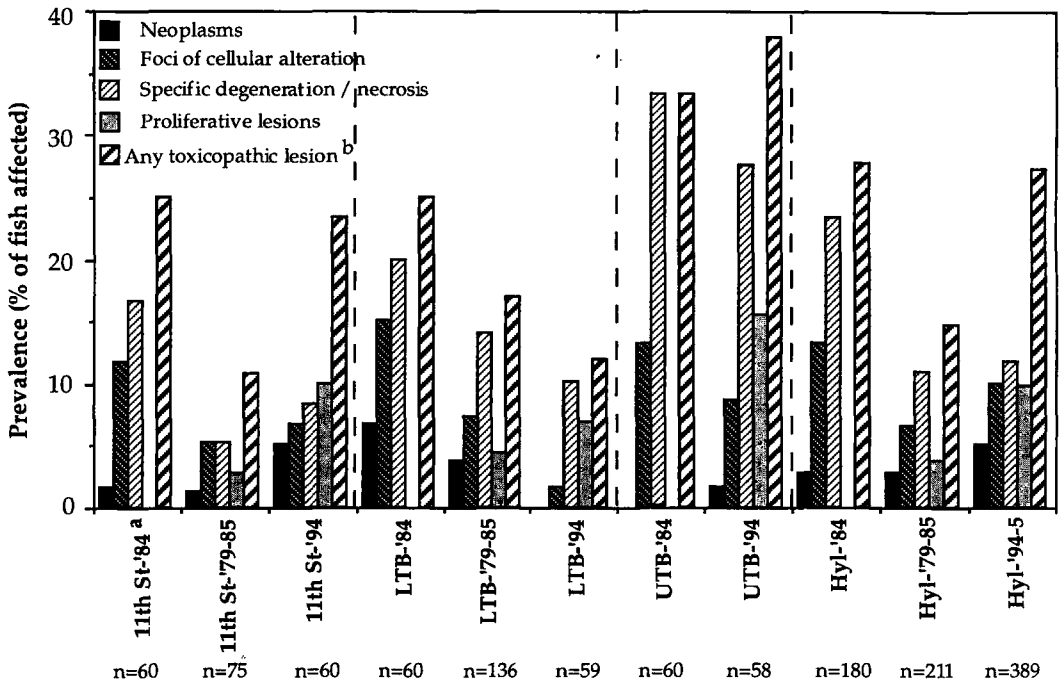

Figure 9. Prevalences of toxicopathic liver lesions in English sole from the Hylebos Waterway in Commencement Bay, Washington, compared to historical data from the Hylebos Waterway.

[a]site abbreviations: 11th St -'94 = 11th St. Bridge site in Hylebos Waterway, 1994; LTB-'94 = lower Turning Basin site in Hylebos Waterway, 1994; UTB-'94 = upper Turning Basin in Hylebos Waterway, 1994; Hyl-'94–5 = combined data from any Hylebos Waterway site, 1994–95; Hyl-'79–85 = combined data from multiple studies done in Hylebos Waterway by NWFSC; 11th St-'84, LTB-'84, UTB-'84 = data from Becker et al. (1987) at the same sites as above.

[b]the "any toxicopathic liver lesion" category includes fish having one or more toxicopathic lesion types including neoplasms, foci of cellular alteration, specific degenerative/necrotic lesions, and proliferative lesions.

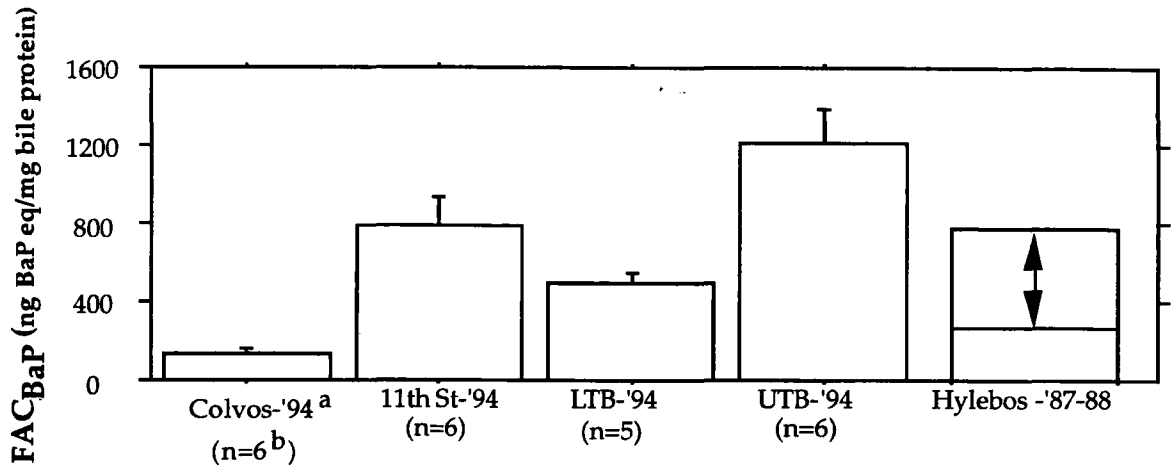

Figure 10. Concentrations of fluorescent aromatic compounds (FACsBaP) in bile of English sole from the Hylebos Waterway in Commencement Bay, and from Colvos Passage, Washington; comparisons with historical data from the Hylebos Waterway. Error bars indicate ± one standard error.

[a]site abbreviations: Colvos-'94 = Colvos Passage, 1994; 11th St-'94 = 11th Street Bridge site in Hylebos Waterway, 1994; LTB-'94 = lower Turning Basin site in Hylebos Waterway, 1994; UTB-'94 = upper Turning Basin site in Hylebos Waterway, 1994; Hylebos-'87–88 = range (indicated by arrows) of mean values determined in 1987–88 (Stein et al., 1992; Myers et al., 1998).

[b]the number of composite analyses conducted is indicated beneath each site name.

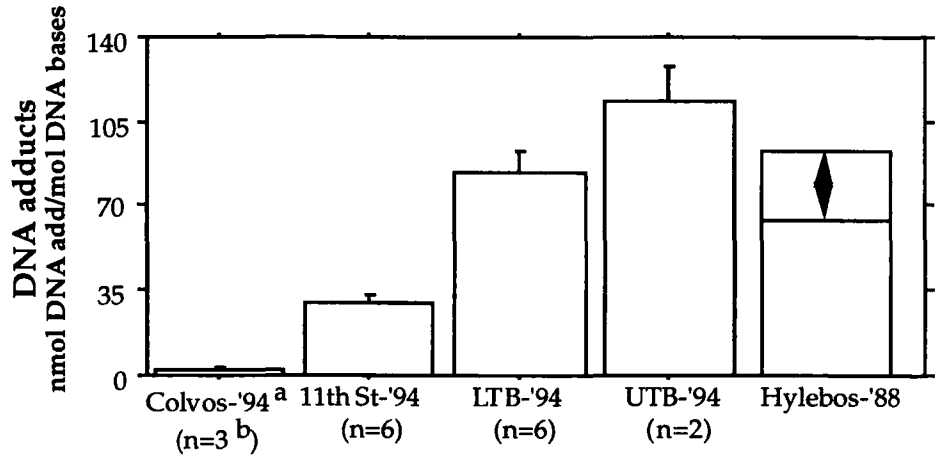

Figure 11. Concentrations of DNA adducts in liver of English sole from the Hylebos Waterway in Commencement Bay and from Colvos Passage, Washington; comparisons with historical data from the Hylebos Waterway. Error bars indicate ± one standard error.

[a]site abbreviations: Colvos-'94 = Colvos Passage, 1994; 11th St-'94 = 11th Street Bridge site in Hylebos Waterway, 1994; LTB-'94 = lower Turning Basin site in Hylebos Waterway, 1994; UTB-'94 = upper Turning Basin site in Hylebos Waterway, 1994; Hylebos-'88 and Hylebos Entrance-'88 = range (indicated by arrows) of values adjusted from previous data (May, 1988; Stein et al., 1992) based on changes in methods for quantifying DNA adduct concentrations.

[b]the number of composite analyses conducted is indicated beneath each site name.

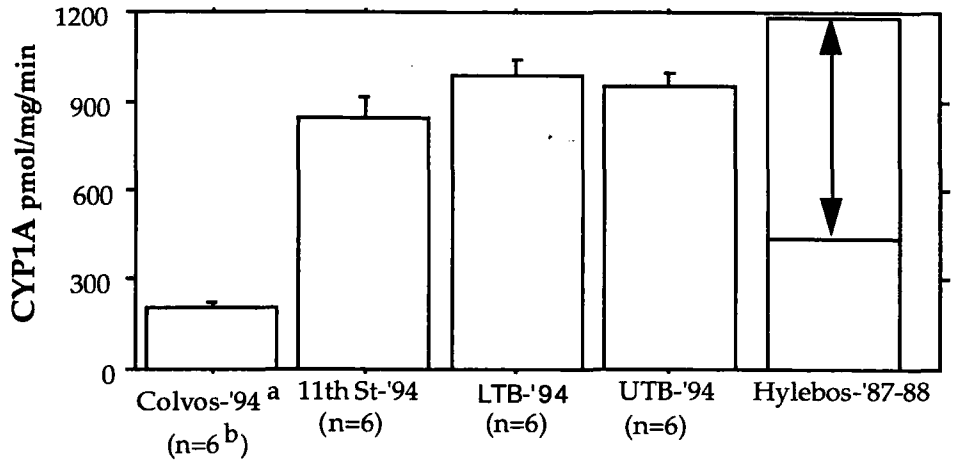

Figure 12. Activities of cytochrome p4501A (CYP1A) in liver of English sole from the Hylebos Waterway in Commencement Bay and in Colvos Passage, Washington; comparisons with historical data from the Hylebos Waterway. Error bars indicate ± one standard error.

[a]site abbreviations: Colvos-'94 = Colvos Passage, 1994; 11th St-'94 = 11th Street Bridge site in Hylebos Waterway, 1994; LTB-'94 = lower Turning Basin site in Hylebos Waterway, 1994; UTB-'94 = upper Turning Basin site in Hylebos Waterway, 1994; Hylebos-'87–88 = range (arrows) of mean values determined in 1987–88 (Stein et al., 1992; Myers et al., 1998). Error bars indicate ± one standard error.

[b]the number of composite analyses conducted is indicated beneath each site name.

Acknowledgements

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Reproductive Anomalies in Bottomfish from the Hylebos Waterway

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Introduction

One of the major environmental issues facing us today is the potential ecological and human-health impacts of chemicals that disrupt the endocrine system (Kavlock et al. 1996). The endocrine system is a network of glands and organs that regulates many bodily functions, including growth, metabolism, reproduction, and immune function, through chemical messengers known as hormones. Endocrine-disrupting chemicals include a broad range of compounds, such as aromatic hydrocarbons derived from fossil fuel products, polychlorinated biphenyls (PCBs), DDTs and other pesticides, surfactants present in detergents, phthalates present in plastic products, and food preservatives. Most of these chemicals interfere with endocrine function by either mimicking or blocking the effects of naturally occurring hormones.

There is considerable evidence that endocrine-disrupting chemicals are affecting the reproductive health of marine fish in the Puget Sound region. In previous studies (Johnson et al. 1988, 1993, 1997; Casillas et al. 1991; Collier et al. 1992), we examined the reproductive function of English sole *(Pleuronectes vetulus)* from selected urban areas in Puget Sound, WA, that were polluted with known or suspected endocrine disruptors, including PCBs and polycyclic aromatic hydrocarbons (PAHs) (Malins et al. 1980). These studies showed that sole from two heavily polluted sites, Eagle Harbor and the Duwamish Waterway, had a variety of reproductive problems, including depressed plasma levels of the female sex steroid, estradiol 17-β, inhibited gonadal development, alterations in egg size and number, spawning inhibition, and reduced egg and larval viability. Although the causative agents were not definitively identified, the aromatic and chlorinated hydrocarbons present in sediments at these sites were significant risk factors for the development of reproductive abnormalities. Laboratory investigations (Stein et al. 1991; Johnson et al. 1995) have subsequently shown effects of similar contaminants on circulating levels of sex hormones in flatfish, which are consistent with field results.

This paper summarizes the results of a field study, initiated in 1994, evaluating reproductive function in English sole from the Hylebos Waterway in Commencement Bay, WA. This waterway is one of the most polluted areas in southern Puget Sound; sediments from this site contain a variety of aromatic and chlorinated compounds, including PAHs and PCBs, as well as other chemicals such as hexachlorobenzene (HCB), which has been identified as a potential reproductive and developmental toxicant in mammals (National Library of Medicine 1992). The Hylebos flatfish reproduction study was one component of a larger effort by trustee agencies to assess the impacts of chemical contamination on several fish species inhabiting this waterway, in order to provide a scientific and legal basis for restoring this degraded habitat (Collier et al. 1998).

Methods

Fish and Sample Collection

Adult female English sole were collected by otter trawl from the Hylebos Waterway and a reference site in Colvos Passage (Figure 1) using the *R/V Harold W. Streeter*. Sampling was conducted approximately every 4–6 weeks from October 1994 through April 1995, during the season when

vitellogenesis normally occurs in this species (Lassuy 1989; Johnson et al. 1991). Approximately 30 fish were collected at each site for every sampling period, and were maintained alive in holding tanks with flowing sea water on board the research vessel until necropsies were performed. Fish were weighed (g) and measured (total length, mm), and otoliths were collected for age determination (Chilton and Beamish 1982). Samples collected included gonad for ovarian histopathology and determination of ovarian maturation stage; liver for organic contaminant and DNA adduct analyses; and bile for measurement of fluorescent aromatic compounds (FACs). Blood was also collected for measurement of plasma 17-β estradiol concentrations, and weights of ovaries, liver, and gutted bodies were collected to determine gonadosomatic, hepatosomatic, and condition indices.

Exposure Assessment

Selected individual liver samples were analyzed using rapid high-performance liquid chromatography with photodiode array detection (HPLC/PDA) for PCB congeners, DDTs and HCB (Krahn et al. 1994). Concentrations of 11 dioxin-like PCB congeners (PCBs 77, 81, 105, 118, 126, 156, 157, 169, 170, 180, and 189), other selected PCBs (PCBs 101, 128, 138, and 153) and chlorinated pesticides (e.g., DDTs, HCB) were determined. To estimate the relative toxicities of the dioxin-like PCBs, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin toxic equivalents (TCDD TEQs) were determined using congener-specific toxic equivalent factors (TEFs) and concentrations of dioxin-like PCBs (Safe 1994).

Biliary fluorescent aromatic compounds (FACs) were analyzed by HPLC as described by Krahn et al. (1986). Biliary FACs were monitored by fluorescence at excitation/emission wavelength pairs for naphthalene (NPH) (290/335 nm), phenanthrene (PHN) (260/380 nm) and benzo[a]pyrene (BaP) (380/430 nm). Levels of FACs were reported as equivalents of known concentrations of BaP, NPH, or PHN standards on the basis of biliary protein (i.e., as ng PAH equivalents per mg biliary protein) because recent studies (Collier and Varanasi 1991) have shown that such normalization can account for variation in FAC levels associated with the feeding status of the sampled fish. Concentrations of biliary protein were determined by the method of Lowry (1951) using bovine serum albumin as the standard. Hepatic xenobiotic DNA adducts were measured using the ^{32}P-postlabelling technique as described by Reichert and French (1994).

Assessment of Reproductive Function

Ovaries were preserved in Deitrichs' fixative for histological assessment. Tissues were embedded in paraffin, sectioned, stained with hematoxylin and eosin and examined microscopically. The ovary was classified into one of the following developmental stages: regressed, late regressed, pre-vitellogenic, vitellogenic, hydrated, spawning, and spent, based on criteria outlined in Johnson et al. (1991) Ovaries were also examined for follicular atresia, hermaphroditism, ovarian macrophage aggregates, and other inflammatory lesions associated with oocyte resorption, including lymphoid or macrophage infiltrates.

For measurement of plasma17-β estradiol concentrations, 1–3 mL blood samples were taken from each fish with a heparinized syringe. Blood samples were centrifuged at 800 G, and the plasma was collected and stored at –80 _C until analyses were conducted. Plasma 17-β estradiol levels were determined by radioimmunoassay (Sower and Schreck 1985).

Somatic indices (gonadosomatic index, GSI; hepatosomatic index, HSI; and condition factor) were calculated as follows:

GSI = (ovary weight [g]/gutted body weight [g]) x 100

HSI = (liver weight [g]/gutted body weight [(g]) x 100

Condition factor = (gutted body weight [g]/length^3 [(cm]) x 100

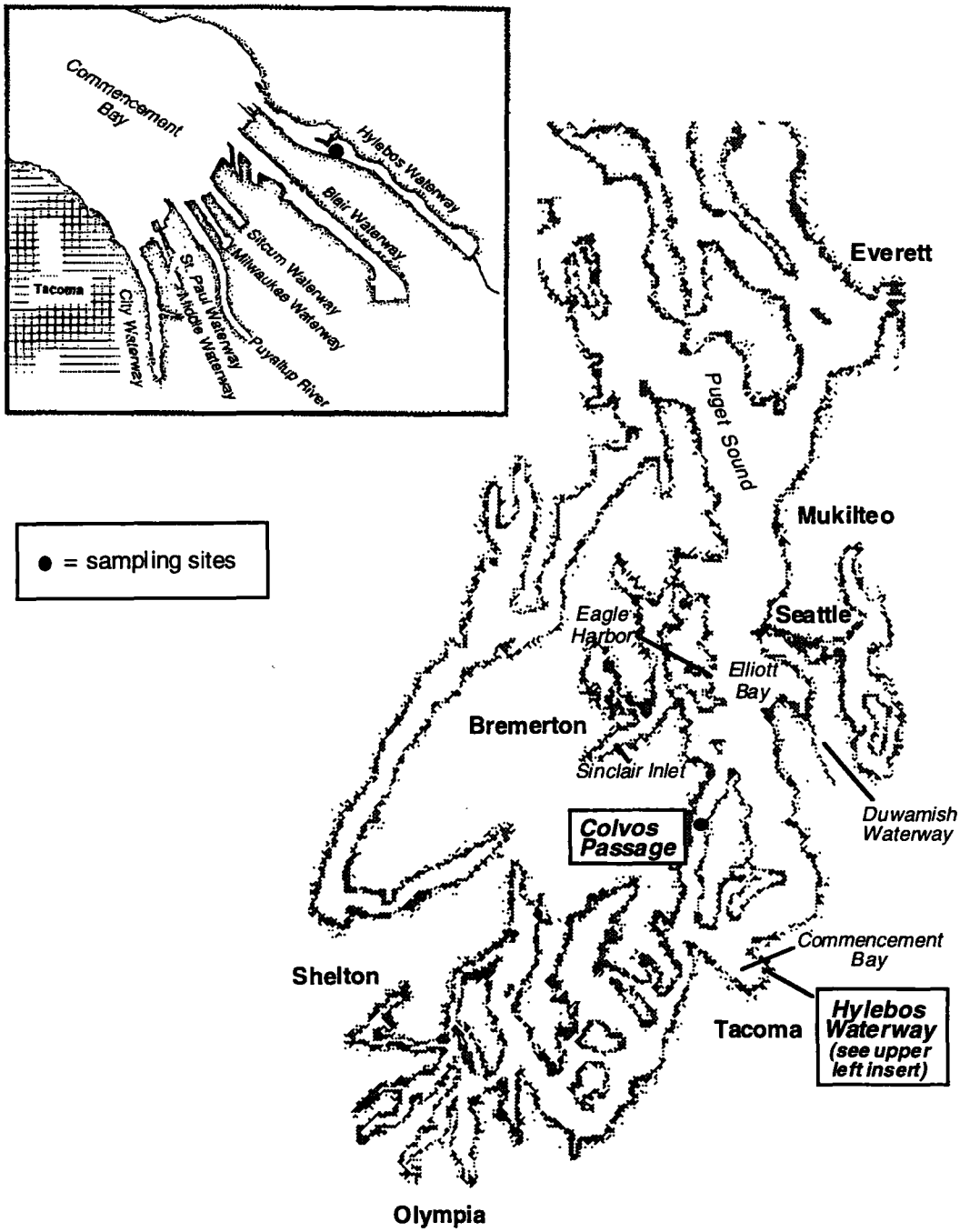

Figure 1. Sampling sites for the flatfish reproductive injury study.

Statistical Analyses

Analysis of variance (ANOVA) was used to identify statistically significant inter-site differences in chemical concentrations and biological parameters. Linear regression analyses and/or Spearman-Rank non-parametric correlation analysis were used to evaluate relationships between bioindicators of exposure (e.g., tissue contaminant concentrations, biliary FACs, DNA adducts) and indicators of biological effects (e.g., plasma estradiol concentrations, GSI, and HSI). For parametric statistical tests such as ANOVA and linear regression, data were normalized through log-transformation prior to analysis. Logistic regression analysis was used to evaluate relationships between binomial or proportional outcome variables (e.g., absence or presence of vitellogenic eggs in the ovary, lesion occurrence). Significance levels (i.e., *p*-values) for individual statistical analyses are reported below in the Results section.

Results

English sole from Hylebos Waterway showed considerably higher exposure to xenobiotic compounds than fish from Colvos Passage. Biliary FAC-BaP, FAC-NPH, and FAC-PHN concentrations were 2–5 times as high in Hylebos Waterway sole as in sole from Colvos Passage; these differences were statistically significant at $p \leq 0.0001$ (Table 1). Levels of DNA adducts in liver tissue, which are an indicator of long-term exposure to aromatic compounds, were also significantly higher in Hylebos Waterway sole than in Colvos Passage sole (Table 1). Concentrations of several classes of chlorinated hydrocarbons, including HCB, DDTs, and PCBs were significantly higher in Hylebos Waterway sole than in Colvos Passage sole (Table 1). In addition to the summed PCB concentration, the mean TCDD TEQ concentration of PCBs (i.e., the concentration of dioxin-like PCBs) was much higher in liver of Hylebos Waterway English sole than in sole from Colvos Passage.

Table 1. Contaminant exposure in English sole from Colvos Passage and the Hylebos Waterway. Significant inter-site differences (1-way ANOVA, $\alpha = 0.05$) are indicated.

	Colvos Passage	Hylebos Waterway	p-value
AH exposure			
FACs-BaP (ng/mg bile protein)	300 ± 70 (59)	770 ± 80 (92)	p = 0.0001
FACs-NPH (ng/mg bile protein)	32,900 ± 2500 (59)	106,800 ± 5500 (92)	p = 0.0001
FACs-PHN (ng/mg bile protein)	8970 ± 2700 (59)	39,500 ± 2200	p = 0.0001
DNA adducts (nmol/mole bases)	5 ± 0.3 (32)	36 ± 5 (48)	p = 0.0001
CH exposure			
SPCBs (ng/g wet wt)	99 ± 8 (48)	1270 ± 240 (56)	p = 0.0001
TCDD equivalents (ng/g wet wt)	3.7 ± 0.3 (48)	36.8 ± 7.1 (56)	p = 0.0001
HCB (ng/g wet wt)	0.9 ± 0.1 (48)	43 ± 5 (56)	p = 0.0001
DDTs (ng/g wet wt)	2.6 ± 0.3	36 ± 9	p = 0.0001

Exposure to chemical contaminants was associated with striking changes in patterns of reproductive development in female English sole sampled from the Hylebos Waterway. Although the timing of the seasonal reproductive cycle was similar in sole from both sites (Figure 2), the proportion of adult females that produced yolked eggs during the peak period of vitellogenesis tended to be lower in the Hylebos Waterway than at Colvos Passage. Overall, approximately 80% (n=44) of adult females (≥300 mm in length or five years of age) from Colvos Passage collected between October and February were undergoing ovarian development, whereas only 58% (n=52) of females of comparable size were developing in the Hylebos Waterway. Both mean GSI and mean plasma 17β-estradiol concentration were significantly lower in adult sole sampled from the Hylebos Waterway during the peak period of gonadal development (October–February) than in sole from Colvos Passage (Table 2). Logistic regression and Spearman-Rank correlation analysis indicated that exposure to aromatic hydrocarbons was the strongest risk factor for inhibited ovarian development (p = 0.0008), reduced GSI and plasma estradiol concentrations (p = 0.02), and ovarian atresia in adult sole (p = 0.004). These findings were very similar to the effects we observed in earlier studies of adult female English sole from the Duwamish Waterway and Eagle Harbor in Puget Sound (Johnson et al. 1988, 1993).

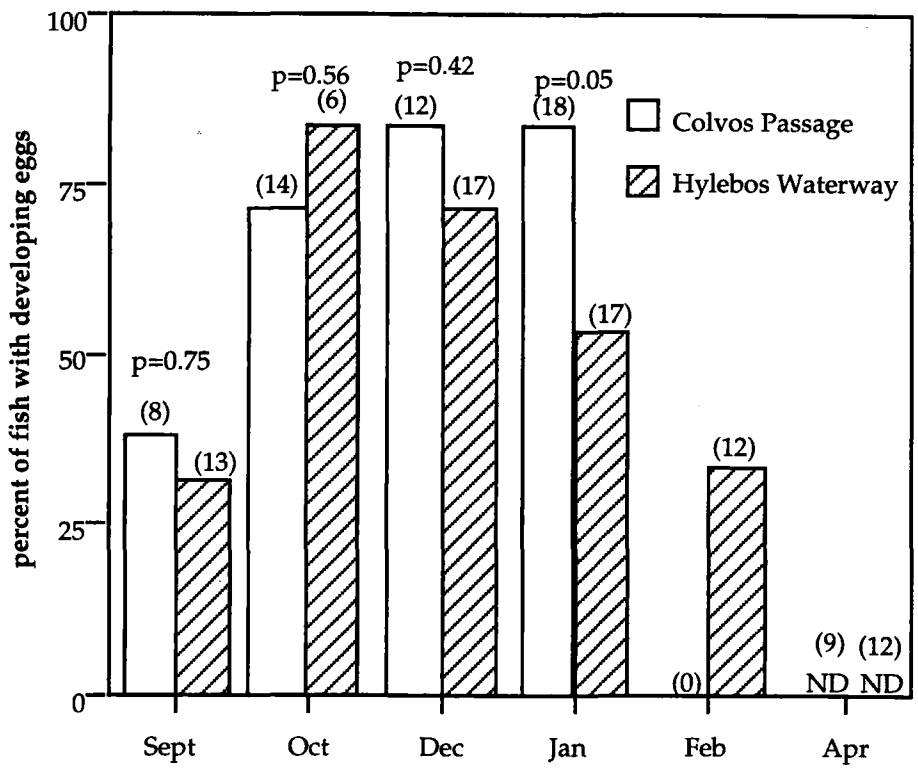

Figure 2. Percentages of female English sole with developing yolked eggs at Colvos Passage and Hylebos Waterway during the 1994 reproductive season. Only adult females of reproductive size (≥300 mm in length) are included in this summary. The number of animals sampled at each time point is given in parentheses. ND = not detected, i.e. no animals with developing eggs were observed. In February no adult female sole were found at Colvos Passage, probably because at this time the fish had migrated to their spawning grounds. The p-values for the statistical comparisons of prevalences of vitellogenic females for at Hylebos and Colvos Passage for each sampling time are shown on the graph.

The strong correlation between PAH exposure and inhibited gonadal development in female sole is consistent with recent reports that these compounds have anti-estrogenic activity because of their properties as Ah-receptor agonists (Gillesby and Zacharewski 1998), as well as with laboratory studies showing inhibited gonadal development and atresia in fish exposed to PAHs (Thomas and Budiantara 1995). Preliminary studies in our laboratory (Anulacion et al. 1997) suggest that extracts of Duwamish Waterway sediments containing high concentrations of PAHs, as well as significant concentrations the TCDD-like and anti-estrogenic PCBs congeners, are effective at suppressing vitellogenin production in English sole pretreated with estradiol. Overall, our observations on Hylebos fish provide strong confirmation of our earlier findings concerning the effects of chemical contaminant exposure on reproductive development in adult female English sole.

Perhaps the most striking finding of this study, however, was the tendency of the Hylebos fish to show precocious maturation (Figure 3). No fish below three years of age showed signs of sexual development at the Colvos Passage site, whereas in the Hylebos Waterway 40–50% of these fish were maturing. Approximately 20% of three-year-old Colvos females were maturing, as compared to 50% of Hylebos females. Logistic regression analysis indicated that Colvos Passage English sole were more likely to undergo reproductive development as they grew older ($p = 0.0001$), at least up to the age of about six or seven, when the proportion of maturing fish stabilized. In Hylebos fish, however, no association between age and probability of reproductive development was found ($p = 0.205$); approximately 50% of sampled females developed, regardless of age class. In sole less than five years of age, mean GSI was significantly higher in Hylebos sole than in Colvos Passage sole (Table 2). Plasma estradiol concentrations also tended to be higher in young Hylebos fish than in young Colvos fish ($p = 0.095$), although the difference was not statistically significant at $\alpha = 0.05$. Because our previous studies of English sole reproductive function in Puget Sound focused specifically on adult sole, we did not observe precocious maturation in these investigations; however, similar effects may be occurring at other sites with sediment contaminant profiles similar to that of the Hylebos Waterway.

Table 2. Mean GSI, plasma estradiol 17-β (E2) concentration, and condition factor in female English sole collected during the 1994 reproductive season (October–February) from Colvos Passage and Hylebos Waterway. Fish are divided into two groups: subadult fish less than five years of age that would be unlikely to mature sexually, and adult fish five years of age and above, which should normally undergo reproductive development.

	Subadult fish (< 5 years old)			Adult fish (> 5 years old)		
	GSI	plasma E2 (pg/mL)	condition factor	GSI	plasma E2 (pg/mL)	condition factor
Colvos Passage	1.82 ± 0.30 (n = 34)	1360 ± 450 (n = 27)	0.73 ±.01 (n = 35)	4.07± 0.42 (n = 45)	3800 ± 580 (n = 45)	0.74 ± 0.01 (n = 44)
Hylebos Waterway	3.12 ± 0.47 (n = 43)	2240 ± 470 (n = 39)	0.79 ± 0.01 (n = 42)	3.49 ± 0.55 (n = 53)	2700 ± 540 (n = 53)	0.74 ± 0.03 (n = 53)
	p = 0.006	p = 0.095	p = 0.0001	p = 0.045	p = 0.003	p = 0.625

The precocious maturation exhibited by Hylebos sole may be partially related to their size, nutritional status, or growth rate, all of which are important cues for the onset of puberty in fish (Le Gac et al. 1993). In fish age five and under, Hylebos fish tended to be about 5–15% larger and have a 5–10% higher condition factor than Colvos fish of the same age (Table 2, Figure 4). However, the average size of Hylebos fish at one and two years of age (240–260 mm) was still smaller than the average length at first reproduction in English sole, which is generally 280–300 mm (Lassuy 1989).

Both aromatic and chlorinated hydrocarbons emerged as potential risk factors for precocious maturation. Of the compounds measured, the strongest risk factor was HCB ($p = 0.0004$), a chemical that is found at particularly high concentrations in the Hylebos Waterway. Although HCB is generally considered a reproductive toxicant (Jarrel et al. 1993), there are cases where it has been shown to stimulate reproductive development. In gastropods, HCB exposure stimulated early egg production (Baturo et al. 1995). At certain stages in the reproductive cycle, it may also increase ovarian weight in rats (Foster et al. 1992). However, other chlorinated hydrocarbons, such as DDTs and PCBs were also significant risk factors for precocious maturation ($0.002 \leq p \leq 0.01$) and could play a role in the development of this abnormality. Indicators of exposure to ACs (biliary FACs and DNA adducts) also showed strong associations with precocious maturation ($0.003 \leq p \leq 0.004$). Most of these indicators of contaminant exposure were also significantly positively correlated with GSI and plasma estradiol concentrations in sole under age five ($0.001 \leq p \leq 0.04$). Because all of these classes of chemicals co-occur in Hylebos Waterway sediments, and fish are exposed to them simultaneously, it is difficult to establish clear cause-and-effect relationships between specific individual chemicals and the reproductive effects observed.

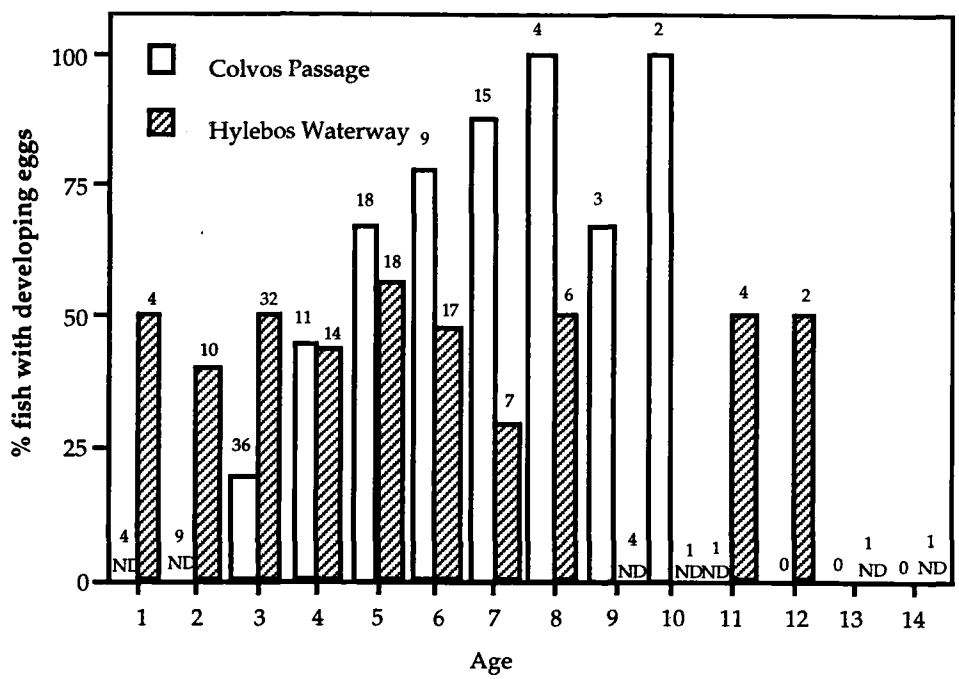

Figure 3. Percentage of maturing female English sole (i.e., sole with developing or vitellogenic eggs) by age class in the Hylebos Waterway and at Colvos Passage. The proportion of fish maturing at ages 1–3 was significantly higher at the Hylebos Waterway than at Colvos Passage, but the proportion maturing at ages five and above was significantly lower.

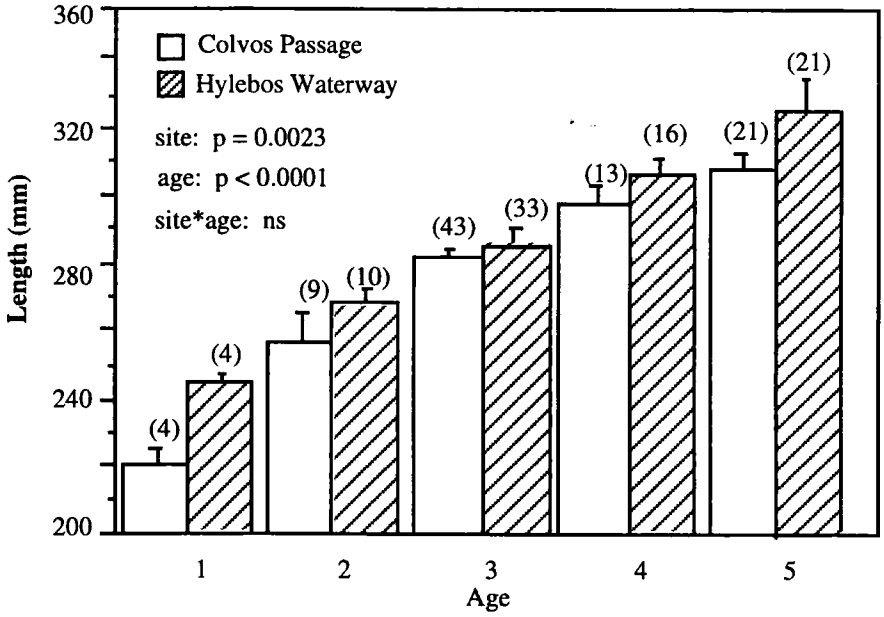

Figure 4. Mean length (+ SE) by age class in female English sole from Colvos Passage and the Hylebos Waterway for animals age 1–5. Younger fish were significantly larger at the Hylebos Waterway than at Colvos Passage. No significant inter-site differences in length at age were observed for fish six years and older (data not shown).

The seemingly contradictory effects of sediment contaminants in the Hylebos Waterway on reproductive development in subadult and adult fish is puzzling, and we have no clear explanation for this phenomenon at the present time. However, the ability of chemical contaminants to stimulate processes such as growth, sexual maturation, and fecundity at low levels of exposure, and inhibit the same processes at high levels of exposure has been demonstrated for a variety of compounds and taxa (Laughlin et al. 1981, Calabrese and Baldwin 1998). For example, although PAHs generally inhibit gonadal development, in starry flounder, exposure to very low concentrations of oil appeared to accelerate egg maturation (Whipple et al. 1978). Similarly, Aroclor (PCB) mixtures at low to moderate concentrations stimulated growth in fetal mice (Marks et al. 1989) and chick embryos (Gould et al. 1997), but inhibited growth at higher doses, probably because of the higher concentration of dioxin-like PCBs in the high dose Aroclor mixtures. Because PCBs are bioaccumulated by English sole, concentrations of PCBs, as well as PCB TEQs tend to increase with fish age. This suggests that the apparent differences in the effects of PCBs on younger and older sole might be due, at least in part, to higher concentrations of dioxin-like PCBs in the older fish.

Several of the contaminants present in the Hylebos Waterway are recognized as endocrine-disrupting compounds, and their stimulatory effects on growth and reproduction in subadult Hylebos sole might be mediated in part through the endocrine system. Several studies have shown that HCB and PCBs can affect thyroid function (van Raaij et al. 1993; Byrne et al. 1987; Ness et al. 1993; Van den Berg et al. 1994; Seo et al. 1995), growth hormone synthesis (Gould et al. 1997), and lipid metabolism (Billi de Catabbi et al. 1997; Bell et al. 1994; Griffin et al. 1994), causing physiological changes that could affect growth, body fat accumulation, and the timing of sexual development. Additionally, some of the chemicals present in the Hylebos Waterway, including DDTs and certain PCB congeners such as PCB 153, have estrogenic activity (Safe 1994; McKinney and Waller 1994) and have been shown to trigger early puberty in rats (Heinrich 1987). There is evidence that other chemicals, such as the dioxin-like PCBs, might stimulate release of gonadotropic hormones in immature females (Li et al. 1997). Studies with mammals indicate that exposure to HCB can alter plasma progesterone levels (Foster et al. 1992, 1995).

In summary, the results of this study indicate that reproductive function is significantly altered in female fish from the Hylebos Waterway, and these changes are associated with exposure to contaminants present in Hylebos Waterway sediments. Aromatic hydrocarbons were most closely associated with inhibited gonadal development in adult sole, while both chlorinated and aromatic compounds are potential risk factors for precocious maturation. Because a complex of factors can influence fish population growth rates, it is difficult to predict with high certainty the consequences of contaminant-related injury to female English sole on sole populations in the Hylebos Waterway and Commencement Bay. However, the altered pattern of reproductive development in Hylebos fish would clearly have an impact on the reproductive output of fish from this site, and could potentially reduce the overall resilience and productivity of the English sole population in Puget Sound in the face of multiple environmental stressors such as overfishing, climate change, or destruction or alteration of nursery or other critical habitats.

Acknowledgments

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Elevated PCB Levels in Puget Sound Harbor Seals (*Phoca vitulina*)

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Introduction

Environmental contaminants including the polychlorinated-biphenyls (PCBs), -dibenzo-*p*-dioxins (PCDDs or dioxins) and -dibenzofurans (PCDFs or furans), persist in environmental compartments as a result of their chemical stability, and bioaccumulate in the food chain because of their fat-soluble nature. While the input of PCDDs and PCDFs into the aquatic environment has primarily been the result of incomplete combustion or as by-products of various industrial processes, the input of PCBs largely reflects the leakage and improper disposal of these manufactured heat-resistant oils. Despite restrictions on their use in the 1970s, PCBs continue to be found at high levels in wildlife species at the top of aquatic and marine food chains (Tillitt et al., 1992; Muir et al., 1992).

Harbor seals (*Phoca vitulina*) have been found to have high levels of contaminants in many parts of the world, including the German Wadden Sea (Skaare et al., 1990), the Baltic Sea (Blomkvist et al., 1992), the United Kingdom (Hall et al., 1992) and central California (Kopec and Harvey, 1995). However, accurate comparisons of results from different studies are difficult, owing to variable sample quality (dead vs. live animals; trauma or illness as cause of death; state of decomposition; age; sex) and the numerous analytical techniques used. When interpreted cautiously, a comparison of different results can be useful as a means of identifying relative degrees of contamination in different harbor seal populations.

Studies carried out in the Netherlands found that captive harbor seals fed herring from the highly contaminated Baltic Sea exhibited immunotoxicity and retinoid disruption when compared to seals fed herring from the relatively uncontaminated Atlantic Ocean (De Swart et al., 1996; Ross et al., 1996a; Ross et al., 1996b). As a result, it is now thought that elevated levels of organochlorine chemicals may have contributed to the severity of the 1988 virus-associated mass mortality of 20,000 harbor seals in northern Europe (De Swart et al., 1995a; Osterhaus et al., 1995; Ross et al., 1996a). In addition, reduced plasma levels of vitamin A and thyroid hormone (De Swart et al., 1995b; Reijnders, 1986), and impaired reproduction (Reijnders, 1986) were observed in captive harbor seals fed contaminated fish.

Because of their high trophic position in the marine ecosystem and their wide geographical distribution, harbor seals can serve as a sentinel species for environmental contamination. It is estimated that approximately 17,000 harbor seals inhabit the inland waters of Washington State, stretching from Port Angeles in the Juan de Fuca Strait, to the southern tip of Puget Sound (Jeffries et al., 1997). Of these, about 1,800 individuals are found in Puget Sound proper (Jeffries et al., 1997). Adult harbor seals in these areas undergo little in the way of migration, and are considered year-round residents of these waters. While harbor seals prefer the lipid-rich herring (*Clupea harengus*) and hake (*Merluccius productus*) as prey items (Olesiuk, 1993), they are opportunistic, and dependent upon local availability, will feed on a wide variety of fish and invertebrate species,. Harbor seals in Puget Sound have been found to be highly omnivorous, with 75% of their estimated average annual diet made up of Pacific cod (*Gadus macrocephalus*), Pacific herring, English sole (*Parophrys vetulus*), Plainfish midshipman (*Porichthys notatus*), and Pacific hake (S. Jeffries, unpublished observations). The complexity of the Puget Sound harbor seal diet may reflect the low abundance of hake and herring compared to the Strait of Georgia, with seals consuming a wide selection of prey items (see Figure 1).

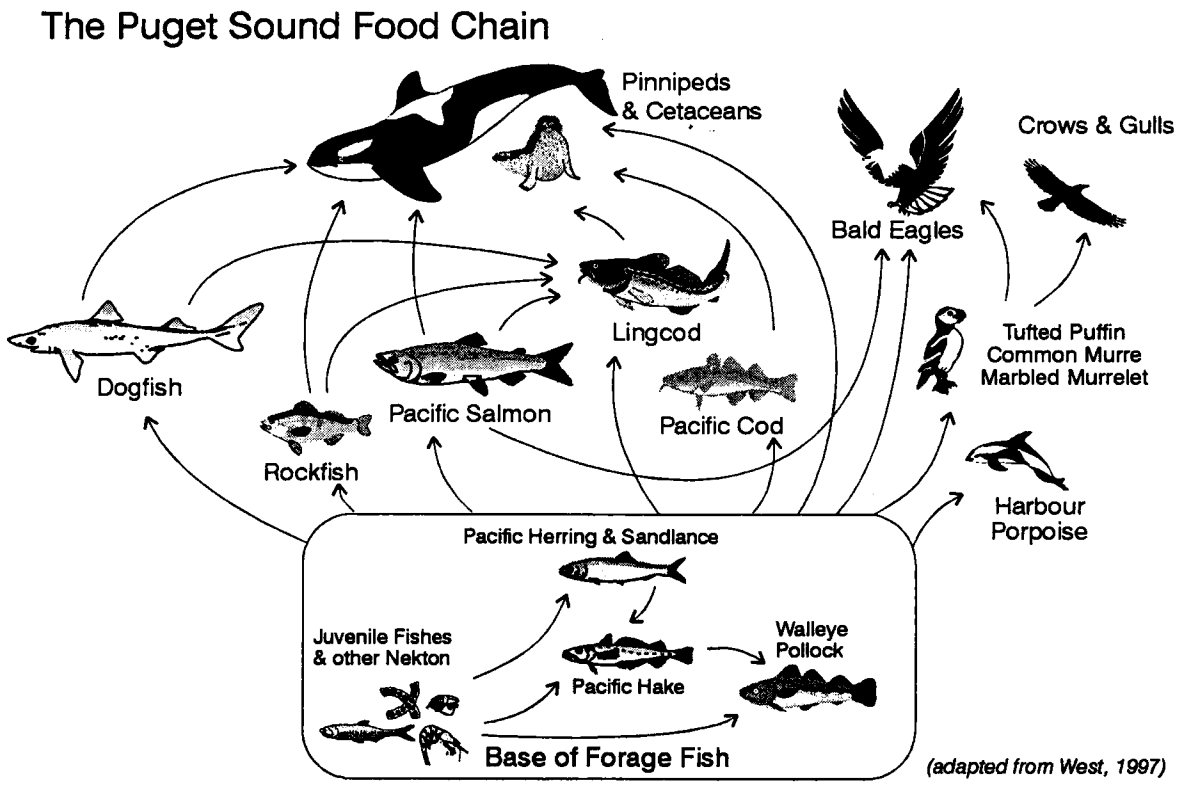

Figure 1. Harbor seals occupy a high trophic level in the Puget Sound ecosystem, and consume a wide variety of different prey species (adapted from West, 1997).

Previous studies have found that harbor seals (Hong et al., 1996; Calambokidis et al., 1991) and other marine mammals (Jarman et al., 1996; Calambokidis et al., 1985) frequenting Puget Sound and adjacent coastal waters of Washington State have high levels of contaminants. While these studies suggest that a regional contamination problem exists, differences in analytical techniques make it difficult to compare these data directly to the results obtained in other areas, or over time.

In order to describe the current levels of PCBs and related PCDDs and PCDFs in Puget Sound harbor seals, we collected blubber samples by biopsy from harbor seal pups on Gertrude Island in 1996. Samples were analyzed by high-resolution gas chromatography-mass spectrometry for all 2,3,7,8-chlorine substituted PCDDs and PCDFs (n=17), as well as all PCB congeners (n=209).

Methods

Blubber samples were obtained from healthy, young harbor seals (n=17), estimated to be four weeks of age, during the breeding season of 1996, from Gertrude Island in south Puget Sound (see Figure 2). Samples were collected by biopsy from live pups caught by beach seine at Gertrude Island. Briefly, a 6-mm disposable biopsy punch was used to obtain a core of skin and blubber (approximately 250 mg) under aseptic conditions from a lateral site above the left hip of the animal. All samples were placed in aluminum foil and stored at –20 _C until analysis.

Approximately 100–200 mg of blubber was used for congener-specific determination of PCBs, PCDDs, and PCDFs at the Regional Dioxin Laboratory (Institute of Ocean Sciences). Blubber samples were homogenized unfrozen and spiked with a mixture of ^{13}C-labeled PCDD/Fs non-ortho, mono-ortho and di-ortho substituted PCB (NO-, MO- and DO-PCB, respectively). The composition of the internal standard spiking solutions, sample extraction procedures, column

chromatographic clean-up and carbon-fiber fractionation of the extracts are described elsewhere (Rantaleinen et al., 1998; MacDonald et al., 1998; Ikonomou, 1998). All fractions collected from the carbon-fiber system were concentrated to less than 10 µL, spiked with the corresponding ^{13}C-labeled method performance standards and analyzed by high-resolution gas chromatography/high-resolution mass spectrometry (HRGC/HRMS). For all analyses the MS was operated at 10,000 resolution under positive electron impact (EI) conditions and data were acquired in the Single Ion Resolving Mode (SIR). Details on the GC and MS conditions are described elsewhere for the PCDD/Fs, and the MO- and NO-PCBs (Rantaleinen et al., 1998; MacDonald et al., 1998) and the DO-PCBs (Ikonomou, 1998). The criteria for identification and quantification and the quality control measures undertaken for the HRGC/HRMS analysis of all the analytes of interest were based on procedures established in the Environment Canada "River Road" protocol (Environment Canada, 1992b; Environment Canada, 1992a) for PCDD/PCDF analysis. The same criteria and quality assurance quality control procedures were also applied to the NO- MO- and DO-PCB analyses. PCB concentrations were calculated by adding the concentrations determined for all 209 congeners.

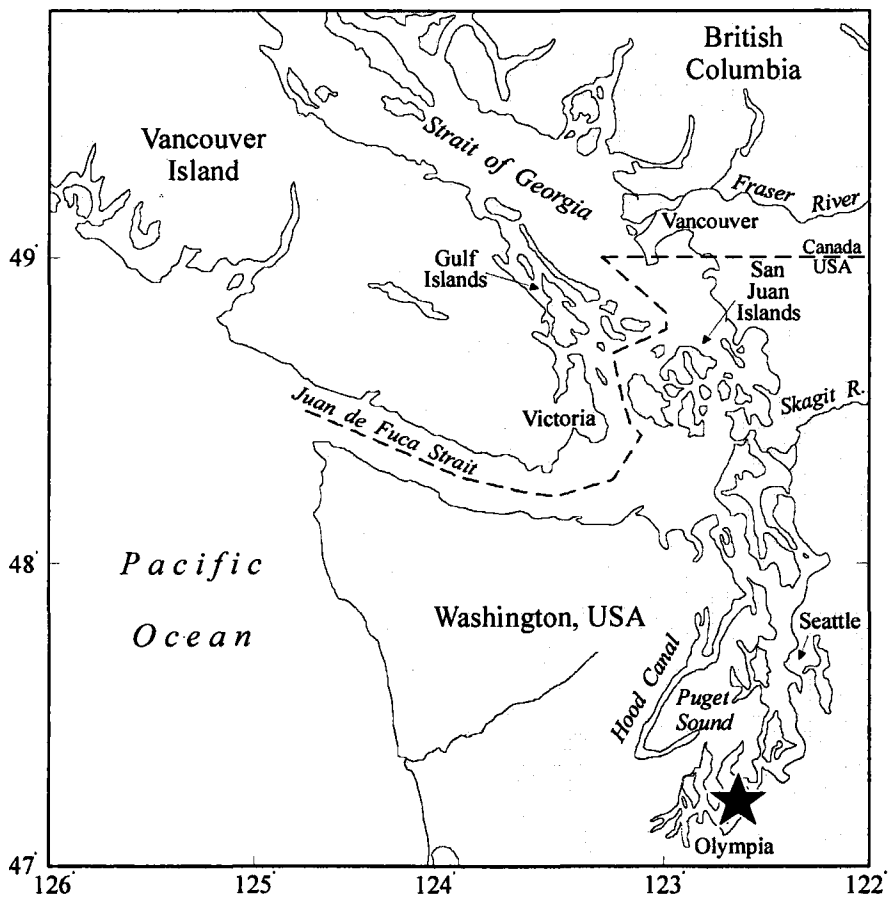

Figure 2. Blubber samples were collected by biopsy from young harbor seals on Gertrude Island in south Puget Sound.

Based on an extrapolation of the PCB-age relationship established for Strait of Georgia harbor seal males and females (Ross et al., 1997) to the mean PCB levels in Puget Sound harbor seal pups in 1996, we modeled PCB dynamics for the Washington State harbor seal population. For this, we used: 1) a correction factor developed by a comparison of mean PCB levels in pups from the Strait of Georgia and pups from Gertrude Island; 2) an extrapolation of the PCB-vs.-age relationship (equations of lines of best

fit) established for the Strait of Georgia harbor seal males and females on the basis of this correction factor; 3) an assumption of a 30% lipid content in harbor seals; and 4) an age distribution for males and females from a population model developed for Strait of Georgia harbor seals (Olesiuk, 1993). On this basis, we estimated the total amount of PCBs present in the approximately 1,763 harbor seals inhabiting Puget Sound proper.

Results and Discussion

Of the three classes of chemicals measured, PCBs represented the predominant contaminant in harbor seal blubber from Puget Sound in 1996, averaging 16.9 ±2.90 mg/kg (lipid weight; mean ±s.e.m.), compared to only very small amounts of PCDDs (141.5 ±18.8 ng/kg lipid weight) and PCDFs (12.3 ±1.5 ng/kg lipid weight). When the concentrations of dioxin-like PCBs, PCDDs and PCDFs are converted to total Toxic Equivalents (TEQ) to 2,3,7,8-TCDD, using international Toxic Equivalency Factors (TEFs)(Ahlborg et al., 1994; Van Zorge et al., 1989), PCBs remain an important contaminant, contributing approximately 95% to the total TEQ in blubber. PCDDs, including the most toxic congener, 2,3,7,8-TCDD, contributed approximately 5%, and PCDFs contributed 1% to the total TEQ. The total TEQ for dioxin-like PCBs, PCDDs, and PCDFs was 167.2 ±27.3 ng/kg (lipid weight).This suggests that PCBs are not only present at very high concentrations relative to the dioxins and furans, but that they also present the greatest "dioxin-like" toxic risk to Puget Sound harbor seals.

Harbor seals represent an important predator at the top of the Puget Sound food chain. They bioaccumulate fat-soluble contaminants including PCBs, PCDDs, and PCDFs, as well as numerous pesticides, from the food chain, and can provide valuable information on the state of contamination of the Puget Sound ecosystem. An understanding of contaminant levels, patterns and trends in harbor seals is relevant to issues of wildlife management, ecosystem health, and human health.

While not conclusive, studies of free-ranging marine mammals have provided circumstantial evidence that ambient levels of environmental contaminants have adversely affected their well-being (see Table 1). The more recent captive-feeding studies involving harbor seals have provided more evidence that contaminants found in fish are immunotoxic and endocrine disrupting (De Swart et al., 1996; Ross et al., 1996a; Ross et al., 1996b). These results provide a means of identifying free-ranging populations of harbor seals or other marine mammals at possible risk.

Table 1: Epidemiological studies that have associated contaminant levels with adverse biological effects in different parts of the world.

Observation	Species	Location	Reference
abortions, premature pupping	California sea lion	California	Delong et al., 1973
tumors, decreased fecundity	Beluga whale	St. Lawrence estuary	Martineau et al., 1987
impaired reproduction	ringed seals	northern Europe	Helle et al., 1976
skeletal lesions	harbor, grey seals	northern Europe	Mortensen et al., 1992; Bergman et al., 1992
reduced testosterone	Dall's porpoises	north Pacific Ocean	Subramanian et al., 1987
diminished T-cell responses	bottlenose dolphins	Gulf of Mexico	Lahvis et al., 1995

Age and sex represent factors that are important when assessing contaminant levels, since males accumulate fat-soluble contaminants throughout their lifetime, whereas females transfer a significant amount of their contaminant burden to their offspring (Aguilar and Borrell, 1994b; Addison and Brodie, 1987). Studies carried out in the Strait of Georgia indicate that such a relationship also exists for west coast harbor seals, with older males being the most contaminated, while older females are relatively uncontaminated (Ross et al., 1997).

On the basis of the PCB levels observed in Puget Sound pups, an extrapolation of the PCB relationship with age and sex observed in Strait of Georgia harbor seals (Ross et al., 1997), and of the

age distribution model from the Strait of Georgia (Olesiuk, 1993), we estimated the total amount of PCBs in Puget Sound harbor seals to be 905 g. The estimated total PCB load of Puget Sound harbor seal males is 699 g, and for females is 206 g, reflecting the loss of these fat-soluble contaminants by females during reproduction and lactation.

Mean levels of PCBs in Puget Sound harbor seal pups were approximately three times higher than those observed in same-age animals inhabiting the Strait of Georgia, British Columbia (Ross et al., 1997). This suggests that the Puget Sound basin remains relatively contaminated with PCBs, in particular, and that the food chain continues to bioaccumulate environmental contaminants.

PCB concentrations observed in 1996 blubber samples from Puget Sound harbor seal pups are similar to the levels found to be immunotoxic in a captive feeding study in the Netherlands (De Swart et al., 1996; Ross et al., 1996a; Ross et al., 1996b), suggesting that contaminant levels continue to represent a tangible concern for this wildlife species. Immunotoxic contaminants are suspected to have played a role in exacerbating recent virus-associated mass mortalities among harbor seals in northern Europe (Osterhaus et al., 1995; De Swart et al., 1995a), striped dolphins in the Mediterranean Sea (Aguilar and Borrell, 1994a), bottlenose dolphins on the east coast of the United States (Kuehl et al., 1991), and Baikal seals in Lake Baikal (Nakata et al., 1995). As such, a potential risk exists for a contaminant-associated immunotoxicity among Puget Sound seals, something that may predispose these animals to a serious outbreak of infectious disease.

Concentrations of PCBs in many wildlife samples declined following the implementation of regulatory controls in the 1970s (Addison et al., 1986), although levels appear to have stabilized in many parts of the world since the mid-1980s (Loganathan et al., 1990). This suggests that PCBs continue to cycle in the environment, and that atmospheric inputs, leaking from former storage sites, and recycling from sediments and the food chain may be preventing a more rapid decrease in these contaminant levels.

This study suggests that PCB levels in young Puget Sound harbor seals are high enough to cause adverse biological effects. Future research should include:

1. continued monitoring of contaminant levels in Gertrude Island harbor seal pups (temporal trends);
2. assessment of contaminant levels in harbor seals inhabiting other inland and coastal waters of Washington State (spatial trends);
3. characterization of the relationship between contaminant levels and age in both male and female harbor seals;
4. research into the possible adverse effects of contaminants on Puget Sound harbor seals; and
5. research into congener-specific contaminant patterns (PCBs, PCDDs, and PCDFs) in the Puget Sound food chain in order to better track contaminant sources and flow through the food chain and identify major routes of contaminants to marine mammals and humans.

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Geographic and Temporal Patterns in Toxicopathic Liver Lesions in English Sole (*Pleuronectes vetulus*) from Puget Sound and Relationships with Contaminant Concentrations in Sediments and Fish Tissues

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Abstract

The Washington Department of Fish and Wildlife, as part of the Puget Sound Ambient Monitoring Program (PSAMP), has monitored the occurrence of toxicopathic liver lesions and contaminant levels in muscle and liver tissue in English sole (*Pleuronectes vetulus*), and sediment contaminant levels at 41 English sole, sampling sites in Puget Sound and the Georgia Basin between 1989–1996. This PSAMP study builds upon research by the Northwest Fisheries Science Center (NWFSC) on sublethal effects of chemical contaminants on flatfish.

As compared to the risk of liver lesion occurrence at 19 non-urban, relatively uncontaminated reference sites (defined as 1.0), sole from urban and near-urban sites showed significantly higher estimated relative risks ranging from 2.0 to 42.0, depending on site and lesion type. Most urban sites showed relative risks in excess of 5.0. Analyses of temporal changes in lesion occurrence at six core sites sampled annually since 1989 showed an apparent increasing trend in overall lesion occurrence in sole from the Strait of Georgia and Elliott Bay. Significant risk factors for liver disease included fish age, sediment PAHs and (to a lesser extent) PCBs, and liver and muscle PCBs. Optimal models of disease risk including these risk factors explained up to 80% of the variation in lesion prevalence. Review of these data suggested liver lesions are first detected at some threshold of exposure to sediment contaminants. Using a two-segment regression model in an analysis of this data set to estimate effects thresholds in English sole for PAHs, most lesions exhibit effects thresholds at 0.5–2 ppm total PAHs in sediment. Overall, these results corroborate and expand upon previous findings by the NWFSC. This thresholding technique may serve as a useful tool for assessing sensitivity to toxicants and for reassessing sediment quality standards using a sublethal end point to account for the impact of chronic exposure to low levels of contaminants on the health of marine organisms.

6B: Toxic Effects

Questions & Answers

Q: What is the state of knowledge today about the impacts of endocrine disrupting chemical, especially the chemicals mentioned today such as the PCBs and the PAHs.

Johnson: I would say that there's very good evidence from wildlife studies and laboratory studies that these chemicals can cause reproductive dysfunction and immune dysfunction, all these effects. I don't think there's much doubt of that. But there's maybe less known about how really widespread this is and whether the problems are more localized I certain areas, or whether it's a more widespread problem. You know, what the population impacts might be I think is not so well known. But there's not much doubt that they can cause a problem.

Q: What I'm concerned about is that regulators want to set some safe levels and I'm just wondering how close to knowing what those levels are?

Ross: It's a tough question. I mean, endocrine disruption is a term that came up, as you know, through Theo Colburn's book last year, and the public seemed surprised by the concept and by the issues, but endocrine disruption as a science has been around for decades. Back to DDT and the effects of eggshell thinning, it was precisely the estrogen-like activities or structure of DDT that led to those effects. So, I think the effects are very, very real, and have played a very, very real part in wildlife toxicology. Many of the fish-eating birds, most of them, were extirpated from North America and Europe through the 1960's and 1970's. And marine mammals, there's a lot of superficial evidence, from captive animals, that marine mammals are being effected around the world and by these chemicals. The problem is, in the real world there's such an incredible mixture of different kinds of chemicals that it's very difficult to pinpoint which one might be responsible for an observed effect. I think true toxicologists like to see single chemical experiments or dosages, but really we need to complement, I think, good laboratory-based science under carefully controlled conditions with good field science, where you do have a good indicator species that is exposed to complex mixtures and go from there. I think the science is improving. I think the confidence is increasing. It's always going to be a difficult one when it comes to legislation or acceptable levels.

Q: Peter, I wanted to ask you whether those harbor seals in Europe that are so contaminated, are they presenting a human health consumption risk. Are peoples, even indigenous peoples eating those?

Ross: In simple terms, they would not. In Canada they would greatly exceed the health Canada guidelines for intake. In fact, most marine mammals anywhere near industrial coastal areas would be unfit for human consumption. And it gets very tricky when you start looking at guidelines for consumption. But currently the most exposed human population on the planet that is getting studied and is being looked at for risk of adverse biological effects to these kinds of chemicals are the Eskimos of northern Canada. They are exposed to levels that area five to ten times higher than southern Canadians were, or the average American. So they are getting exposed to very high levels, not because the arctic is very contaminated, but just because they are eating at a higher position on the food chain, and part of the diet are seals and marine mammals. And the levels that observe or that we see in humans, if we take blood sample or a lipid sample and look at PCBs and other chemicals, are high enough to warrant some serious concern about human health. And that's in the Canadian arctic.

PUGET SOUND RESEARCH '98

SESSION 6C

MARINE BIOLOGICAL COMMUNITIES

Session Chair:

Bill Dewey

Taylor United, Inc.

Biocriteria for Puget Sound: A Summary of Phases I Through III

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Introduction

Development of biocriteria depends on the premise that population and condition parameters of marine biota provide a sensitive screening tool for assessing the condition of a water resource (M.L. Bowman et. al., 1997). The purpose of the biocriteria effort is to incorporate biotic health and ecological metrics derived from the sampling of multiple biological assemblages into a broad-based index using natural reference conditions as benchmarks—the biocriteria. Once biocriteria are developed, based on minimally impaired reference conditions, sites are evaluated to determine how well they measure up against the criteria. The greater the discrepancy, the greater the potential impairment of the water resource. The biocriteria should be carefully developed so as to closely represent the natural biota, provide the sensitivity to identify marginally disturbed sites, protect areas against further degradation, and stimulate restoration of degraded sites. These biological measures should be based on sound scientific principles that are quantifiable and written to protect or enhance the designated use. To account for a measure's natural variability in a healthy environment, the criterion should be designed to accommodate seasonality and should be defined as a range rather than as a discrete value, often represented graphically as box plots. By linking the assessment and cleanup of environmental impairment to a biological index, the goal is to make the evaluation process not only much more meaningful—both socially and ecologically—but also much more economical.

The three phases of the Puget Sound biocriteria pilot study (Eaton and Dinnel 1993; Eaton 1994, 1995) is a part of the national developmental research effort funded by EPA headquarters designed to construct meaningful biocriteria/bioassessment metrics for measuring environmental impairment and cleanup goals. Two years of research were conducted in the Tacoma area in 1993 and 1994 (Phases I and II) and in Sinclair Inlet, Port Orchard and Quartermaster Harbor in 1997 (Phase III) to develop and assess the sampling methods for three biological assemblages: demersal fish, epibenthic macroinvertebrates, and macrobenthos. The pilot studies assessed the utility of using two different trawls (the 7.6-m otter trawl and the 3-m beam trawl) and a 0.2-m^2 van Veen sediment sampler with multiple sample replications to define demersal populations of marine fishes and epibenthic and infaunal invertebrates. Using the documented population patterns and comparisons between reference and contaminated stations, the study objectives were ultimately to:

- gain a greater understanding of how demersal populations are being affected by pollution and habitat degradation;
- determine which biological patterns reflect environmental stress; and
- develop prototype biological metrics from the data that would help to build a biological index for the rapid and economical assessment of stress in subtidal biotic marine communities.

Quantitative methods of economically sampling three different biological assemblages representing three different scales of analysis have now been developed:

1. Demersal fishes using the 7.6-m SCCWRP otter trawl.
2. Epibenthos using the 3-m Gunderson beam trawl.
3. Macrobenthic infauna using the 0.2-m^2 van Veen sampler and 4-mm-mesh screen.

Phase I: Hylebos Waterway vs. Blair Waterway (1993)

Study and Sampling Design

The demersal fishes and epibenthos of the contaminated Hylebos Waterway were compared to the relatively clean and adjacent Blair Waterway in Tacoma in June of 1993 (Eaton and Dinnel, 1993) using a stratified random design. The demersal fishes and epibenthos were sampled in Phase I using the otter trawl and beam trawl, respectively. All catches were kept alive and processed onboard—catch and release sampling. Although lengths were recorded on many individuals, biomass data were not collected in Phase I.

Results of Phase I

This initial effort at defining biocriteria led to several conclusions:

- Tolerant species found in greater or insignificantly different abundance in the Hylebos Waterway compared to the Blair Waterway and confirmed by limited sampling in contaminated Eagle Harbor included:

English sole	rock Sole	sand Sole
speckled sanddab	Pacific tomcod	pygmy poacher
snake pricklebacks	sculpins (especially staghorn sculpins)	cancer crabs (especially *C. gracilis*)
coonstripe shrimp	crangon shrimp?	sea anemones
Evasterias spp. (sea star)		

- Sensitive species found in significantly greater numbers in the Blair Waterway compared to the Hylebos Waterway included:

  juvenile blackbelly eelpouts (BT) — juvenile bay gobies (BT)

  sea cucumber (*Parastichopus californicus*)

- Significantly larger size categories for the Blair Waterway compared to the Hylebos Waterway included:

  male English sole — purple shore crab (*Cancer gracilis*)

  Pacific tomcod, juvenile & adult

- Raw or averaged abundance and diversity data were not valuable in distinguishing the contaminated and reference sites. Length/weight regressions (WAL) for male English sole were essentially identical between the waterways.

- External health indices such as dead *Crangon* eggs, microsporidian infections, fish lesions and bloodworms (*Philometra*) were not useful in differentiating the test site from the Blair reference site.

- Five sample replications were recommended for the 7.6-m otter trawl.

Phase II: Thea Foss Waterway vs. Quartermaster Harbor (1994)

The conclusion drawn from Phase I indicated that raw or averaged abundance data were not useful in differentiating contaminated sites from reference sites. This fact led to an increased effort in recording biomass data in Phase II, and to the study of a more natural reference condition than was represented by the Blair Waterway in Phase I.

Study and Sampling Design

The coverage of the results from Phase II focused on the best-matched comparison of the QMH 1 reference station in upper Quartermaster Harbor and the contaminated TF 1 station in the upper end of the Thea Foss Waterway. The average grain size of surface sediments along the 1994 TF 1 trawl path was reported by Tetra Tech (1985) at 78% fines. This result closely matches the grain-size analysis at QMH 1 (80% fines) using the wet-sieving technique. Bottom temperatures (14 _C) were identical at both stations on 11 September 1994, and bottom salinities were closely matched with 31 ppt at TF 1 compared to 32 ppt at QMH 1. Bottom depth (MLLW) is only slightly deeper at QMH 1 (6 m) than at TF 1 (5 m). Despite these physical similarities at a point in time (late summer), it may be that the sites are not within the same class when compared seasonally. The proximity of the Puyallup River plume to the Thea Foss Waterway may contribute to annual salinity and turbidity differences unnoticed in September during low water runoff, and may reduce the validity of the comparison. It should be pointed out, also, that it is unrealistic to expect a cleanup effort in the Thea Foss Waterway to approach the biocriteria measured in Quartermaster Harbor with its larger size and natural shoreline. More valid biocriteria goals would be obtained from cleaner waterways such as the Blair or the Sitcum.

Results of Phase II

Despite these caveats, the comparison still proved to be an interesting one, and several conclusions from Phase I were reinforced in the Phase II comparison:

- Tolerant Species common to both Phase I and Phase II:

English sole	sand sole	Pacific tomcod
snake pricklebacks	Sculpins (especially staghorn sculpins)	cancer crabs (especially *C. gracilis*)
coonstripe shrimp	crangon shrimp	sea anemones
Evasterias (sea star)		

- Sensitive species common to both Phase I and Phase II:

bay goby (BT)	blackbelly eelpout (BT)	sea cucumbers

By sampling in a more natural reference area, several additional sensitive species were added to the list in Phase II:

- Sensitive species added in Phase II:

large starry flounder	pile surfperch	striped surfperch
bay pipefish	cartilaginous fishes (skates, ratfishes and dogfishes)	

Results of the second year of sampling emphasized the ecologically important fact that the reference site, despite fewer or equal numbers of fishes, supported more than twice the fish biomass than the contaminated site. Almost every fish species common to both areas was significantly larger, and fish species richness and evenness were significantly higher at the reference site. At the same time, a better comparison of impaired and reference conditions needed to be designed, one in which there would be no doubt that the reference condition was of the same physical class and supporting the same biological community as the test site.

Phase III: Sinclair Inlet, Upper Port Orchard, and Quartermaster Harbor

Objectives of Phase III

The primary objectives of the Phase III 1997 study were to test the preliminary trawl metrics developed in Phases I and II by using them in other areas, and to test their resolution by comparing a more moderately contaminated test site, Sinclair Inlet, to multiple reference sites from within the same class—Port Orchard and Quartermaster Harbor (Figure 1).

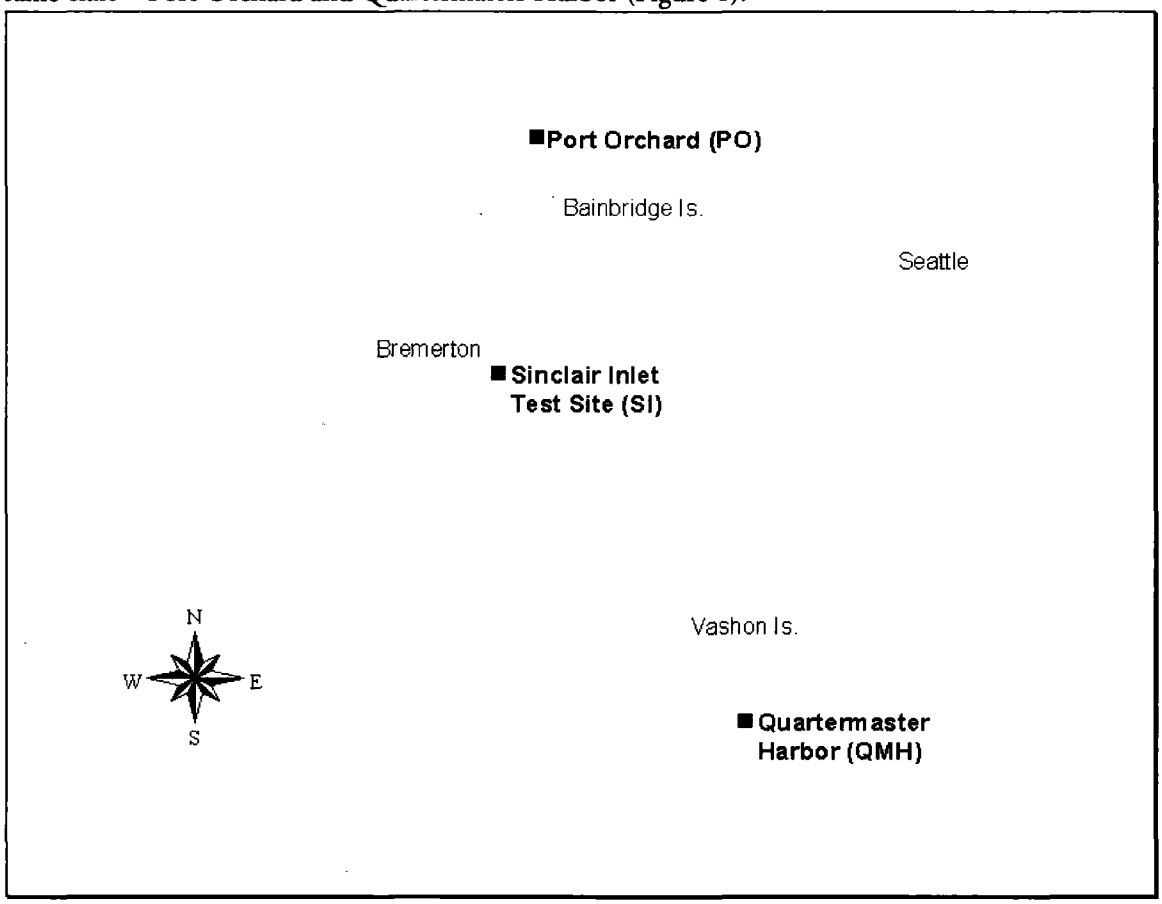

Figure 1. Study sites for Phase III. Two strata from the Sinclair Inlet test site (SI) were compared to strata from multiple reference sites of the same depth and sediment grain size in Port Orchard (PO) and Quartermaster Harbor (QMH). The benthic infaunal assemblage from QMH was not the same community as was found in the SI test site or the PO reference site. This fact precluded the use of QMH in the definition of the reference condition for Sinclair Inlet. A measurement of interannual variation in the demersal fish community was accomplished in QMH by comparing 10 replicate otter trawls from September 1997 to 11 trawls in same location from September 1994

The second objective of the 1997 field sampling was to develop another economical sampling technique for an additional biological assemblage. The macrobenthic infaunal assemblage was chosen by testing the efficacy of using 10 replicate samples per stratum with a 0.2-m^2 van Veen sampler, screening the samples through 4-mm mesh screen, and processing the samples onboard. Ten to 15 samples per day could be collected and processed using this method.

The Sinclair Inlet test site, offshore of the Puget Sound Navel Shipyard, is known to have environmental problems similar to those found in Dyes Inlet, but not to the degree of the Hylebos

and Thea Foss Waterways used in the Phase I and Phase II studies. The study area has never been dredged, and most of Sinclair Inlet still has a natural intertidal zone. The primary problem, as discussed in the PSAMP draft report from WDOE (Llanso et. al., 1998) are exceedences of the Sediment Quality Standards (SQS) for arsenic and mercury, and exceedences of the Apparent Effects Threshold (AET) for benzyl alcohol and PCBs. Eleven other compounds have been detected by the Marine Sediment Monitoring Program (MSMP) above the Effects Range-Low (ER-L) including seven other metals and total PAH. These are pollutants for which biological effects may occur occasionally (Long et al., 1995).

Johnson et. al. (1995) reported that reproductive impairment and non-fishing mortality were higher for English sole from contaminated sites in Puget Sound, including Sinclair Inlet, than from the Port Susan reference area. Mortality rates for English sole from Sinclair Inlet were surprisingly higher than those found in the more organically-contaminated Eagle Harbor Superfund site, and were comparable to those measured from the more contaminated Duwamish Waterway, despite the fact that the reported prevalence of toxicopathic disease in English sole from Sinclair Inlet was considerably lower than was encountered at either Eagle Harbor or the Duwamish Waterway (Malins et al., 1984; Johnson et al., 1988; Myers et al., 1990). Finally, the PSAMP Fish Task has reported elevated levels of lead and PCBs in tissues of English sole from the Sinclair Inlet test site (O'Neill et al., 1995).

Study and Sampling Design

- A new study design was initiated in 1997 that divided the test and reference areas into strata of approximately 350,000 m^2 whose boundaries were defined by restricted depth and sediment grain size ranges, and within which replicate samples were randomly located using Microsoft Excel's random number generator and NavTrek 97™ navigation software. Sampling took place in late summer of 1997 from August 19th to September 13th. Only the fish assemblage (otter trawl) and the macrobenthos (0.2-m^2 van Veen) were sampled. All samples were processed live onboard and released on stratum. Most fish species were processed as two groups—adults and subadults. Lengths and biomass data were recorded for all species—some as group weights, others as individual weights. Because of funding restraints, only two of the four initial strata were sampled:

- Stratum III: 11–14 m (MLLW); mean grain size = 80% fines (75%–83%); mean sediment temperature = 14.1 _C (Sinclair Inlet & Port Orchard), 13.0 _C Quartermaster Harbor; mean salinity = 30 ppt (Sinclair Inlet & Port Orchard), 31 ppt Quartermaster Harbor.

- Stratum IV: 14–18.3 m (MLLW); mean grain size = 73% (64%–78%) fines for Sinclair Inlet and Port Orchard, 78% fines for Quartermaster Harbor (74%–81%); mean sediment temperature = 14.1 _C (Sinclair Inlet & Port Orchard), 13.1 _C Quartermaster Harbor; mean salinity = 29.5 ppt (Sinclair Inlet & Port Orchard), 32 ppt Quartermaster Harbor.

In summary, Stratum IV is slightly deeper with a slightly coarser grain size than Stratum III. Quartermaster Harbor (QMH) was not as well matched to the Sinclair Inlet (SI) test site as was Port Orchard (PO), because Quartermaster Harbor had slightly finer sediments in Stratum IV (78% vs. 73%), slightly colder temperatures (13.1 _C. vs. 14.1 _C.), and slightly higher bottom salinities. It was also immediately apparent upon sampling the benthic infauna that Quartermaster Harbor, despite its reasonably well matched physical parameters to Sinclair Inlet and Port Orchard, did not represent a comparable biological community—the ultimate test of the physical classification. The deposit-feeding bivalve molluscs, so prominent in our samples from Sinclair Inlet and Port Orchard, were almost absent from the QMH samples. No burrowing anemones (*Pachycerianthus*) or sipunculids (*Golfingia*) could be found. Large deposit-feeding bamboo worms (maldanidae) dominated the QMH samples but were extremely rare in the SI and PO samples. This lack of a

good pairing frustrated one of the primary objectives of the Phase III sampling: to compare the Sinclair Inlet test site to multiple reference sites from within the same class. On the other hand, the upper Port Orchard reference site represented the best pairing to a test site ever obtained in the three phases of the biocriteria/bioassessment sampling. Therefore, the results of the Sinclair Inlet/Port Orchard pairing will be emphasized in the discussion, along with the interannual variation in the Quartermaster Harbor demersal fish sampling from September 1994 versus September 1997.

The voluminous population data were entered into Excel 7.0 spreadsheets and then initially scanned as bar graphs. This data was then transferred to a statistical software package, SPSS/Windows, where potentially interesting patterns were graphed as box plots to help visualize the distribution of the variable (Figures 2–5). Box plots were chosen because of their ability to visually represent the central tendency of a range of data generated by replicate sampling. The box itself, called the interquartile range (IQR), represents 50% of all cases and extends from the 25th to the 75th percentile with the horizontal line representing the median value (50th percentile). The vertical lines (whiskers) are drawn to the largest and smallest values that are outside the box but within 1.5 box lengths, and represent the range of data not considered to be outlying or extreme. Outliers (o) lie within 1.5–3 box lengths from the upper and lower edges of the box, and extreme values (*) are more than three box lengths from the upper and lower edges. The central tendency is represented by the median (the horizontal line within the box), the spread or variability by the length of the box and whiskers, and the symmetry of the spread by the position of the median line within the box. If the median line is closer to the bottom of the box than to the top, there is a tail toward the larger values (positive skewness) or vice versa, with the length of the tail shown by the length of the box and the length of the whiskers and the outlying and extreme values. The biocriteria are often defined visually by the box plots themselves, with the lower edge of the box (the 25th percentile) for the displayed metric variable from the reference areas serving as the goal or criterion. In a monitoring or cleanup effort, the target median of the test site variable or index would be this 25th percentile reference value.

Results of Phase III

Demersal Fish Populations

Many of the premises developed in the Phase I and Phase II sampling were confirmed in the comparison of the Sinclair Inlet test site to the upper Port Orchard reference site (Table 1, Figures 2–3) including the following:

- Fish biomass was much lower at the test site compared to the reference site (Figure 2).
- Flatfish biomass was much lower at the test site compared to the reference site (Figure 2).
- Starry flounder, cartilaginous fishes, subadult flatfish, and Pacific herring biomass and abundance were greatly reduced at the Sinclair Inlet test site (Figure 2, cont.).
- English sole, sand sole, the common sculpins (especially staghorn sculpin) and juvenile (subadult) Pacific tomcod, snake pricklebacks and shiner surfperch were all confirmed to be tolerant species.
- Starry flounder, cartilaginous fishes, and giant sea cucumber once again appeared to be sensitive species.
- Tolerant flatfish abundance and biomass (especially English sole) were numerically slightly higher and more variable at the test site than at the reference site (Figure 3).
- Common sculpins (staghorn, northern, and roughback) abundance and biomass were elevated at the test site relative to the reference site (Figure 3).

In addition to the confirmed premises above, the following additional characteristics that had not been previously noted in Phases I and II separated the test site from the Port Orchard reference site:

- Total fish abundance was reduced at the test site (Figure 2).
- Flatfish abundance was reduced at the test site (Figure 2). Previously, abundance data had not been useful in differentiating sites.
- Subadult flatfish abundance and biomass were greatly reduced at the test site (Figure 2, cont.).
- Rock sole, speckled sanddabs, and plainfin midshipmen rejoined the list of tolerant species where they had been placed during Phase I.
- Adult Pacific tomcod, snake pricklebacks and shiner surfperch (unlike their subadults) were reduced at the test site. This may have been first noted this year because of the additional effort of separating adult and subadult individuals during onboard processing.
- Adult bay gobies from the otter trawl catches were numerically more abundant at the test site than at the reference sites, and should be considered a tolerant group. In past sampling, juvenile bay gobies (sampled in the beam trawl, not used in Phase III) were significantly reduced at the impaired sites (Hylebos and Thea Foss Waterways) and are still considered a sensitive indicator.
- Even though flatfish biomass (Figure 2) and flatfish mean individual weights were significantly lower at the impaired site compared to the reference sites, the mean individual weights of adult English sole (Figure 3) and rock sole from Sinclair Inlet were higher than those from Port Orchard. This may reflect a release from competition with large starry flounder which were almost absent from the test site and which make up the bulk of the flatfish biomass from Port Orchard.
- Although adult Pacific tomcod were numerically reduced at the test site compared to both reference sites, the mean individual weights of these adults were much higher at the test site, unlike the results from the Phase I and Phase II studies.
- The derived metrics of richness, dominanc, and evenness displayed no significant differences between the test site and the Port Orchard reference site (Figure 4), as was also found in the Phase I comparison but not in Phase II.

Table 1. A summary evaluation of trawl metrics and the apparent response to environmental impairment.

Apparent Response to Impairment

BT = Beam Trawl, epibenthos, and small fishes
OT = Otter Trawl, larger demersal fishes

Candidate Metric	1993: **Hylebos vs. Blair Wtys.** Caveat: Hylebos has much more wood debris than Blair	1994: **Thea Foss vs. QMH** Caveat: QMH may not be an ideal ref. for Thea Foss	1997: **SI vs. Port Orchard** The best comparison	1998: **Predicted Response:**	**Useful Metric?**
Demersal fish abundance per unit area (OT)	No significant difference	Increase or no difference	Decrease	Decrease or no difference	?
Demersal fish biomass per unit area (OT & BT)		Decrease	Decrease	Decrease	Yes
Total flatfish biomass (OT)		Decrease	Decrease	Decrease	Yes
Subadult flatfish abundance and biomass (OT)			Decrease	Decrease or no difference	Yes
Starry Flounder abundance & biomass (OT)		Decrease	Decrease	Decrease	Yes
Rock Sole abundance and biomass (OT)	No significant difference	Decrease	No significant difference	No difference	No
English Sole abundance & biomass (OT)	No significant difference	Increase	Increase	Increase or no difference	No
Bay Goby abundance and biomass (BT)	Decrease	Decrease		Decrease	Yes
Cartilaginous fish abundance and biomass (OT)		Decrease	Decrease	Decrease	Yes
Pacific Staghorn Sculpin abundance and biomass (BT)	Increase	Increase	Increase (OT)	Increase	Yes
Subadult Pacific Tomcod abundance & biomass (OT)	No significant difference	Increase	No significant difference	No significant difference	No
Adult Pacific Tomcod abundance & biomass (OT)	No significant difference	No significant difference	Adults Decrease?	Decrease or no differençe	?
Fish Mean individual weights	Depends on species	Decrease	Depends on species	Depends on species	No
Fish Weight / Length Ratio	No significant difference		No significant difference	No significant difference	
Pacific Staghorn Sculpin mean individual weights (OT)		Increase	No significant difference	No significant difference	No
Adult Shiner Surfperch abundance and biomass (OT)		Increase or no difference	Decrease	Decrease or no difference	No
Subadult Shiner Surfperch abundance and biomass (OT)			Increase	Increase	?
Snake Prickleback abundance (OT)	No significant difference	No significant difference	Decrease	No significant difference	No
Snake Prickleback abundance (BT)	Increase	No significant difference	No data	No significant difference	No
Adult Snake Prickleback abundance (OT)			Decrease	Decrease or no difference	No
Subadult Snake Prickleback abundance (OT)			No significant difference	No difference or increase	No
Sea cucumber abundance and biomass (OT&BT)	No data	Decrease	Decrease	Decrease	Yes

Table 1 (continued). A summary evaluation of trawl metrics and the apparent response to environmental impairment.

Apparent Response to Impairment

BT = Beam Trawl, epibenthos and small fishes
OT = Otter Trawl, larger demersal fishes

Candidate Metric	1993: **Hylebos vs. Blair Wtys.** Caveat: Hylebos has much more wood debris than Blair	1994: **Thea Foss vs. QMH** Caveat: QMH may not be an ideal ref. for Thea Foss	1997: **SI vs. Port Orchard** The best comparison	1998: **Predicted Response:**	**Useful Metric ?**
Sensitivity Index (Sensitive / Sensitive + Tolerant)	Decrease	Decrease	Decrease	Decrease	Yes
Total species richness	No significant difference	Decrease or no difference	No difference	No difference	No
Dominance and Evenness	Not analyzed	Decrease or no difference	No significant difference	No significant difference	No
External fish abnormalities	No significant difference	No significant difference	No significant difference	No significant difference	No
Crustacean abundance and biomass (BT)	Increase	Increase	No data	Increase	Yes
Cancer crab abundance and biomass (BT)	Increase	Increase	No data	Increase	Yes
Cancer gracilis abundance and biomass (BT)	Increase	Increase	No data	Increase	Yes
Evasterias troschelli (mottled seastar) abundance (BT)	Increase	Increase	No data	Increase (debris-dependent)	No
Pile anemone abundance and biomass (BT)	Increase	Increase	No data	Increase (debris-dependent)	No
Mean Individual Weights:					
Adult Flatfish as a group	No data	Decrease	Decrease	Decrease	Yes
Adult English Sole	Decrease	Decrease	Increase	Unknown	No
Adult Rock Sole	No significant difference	Decrease	Increase	Unknown	No
Shiner Surfperch	No data	Decrease	Increase	Unknown	No
Adult Pacific Tomcod	Decrease	Decrease	Increase	Unknown	No
Staghorn Sculpins	No significant difference	Increase	No significant difference	No significant difference	No

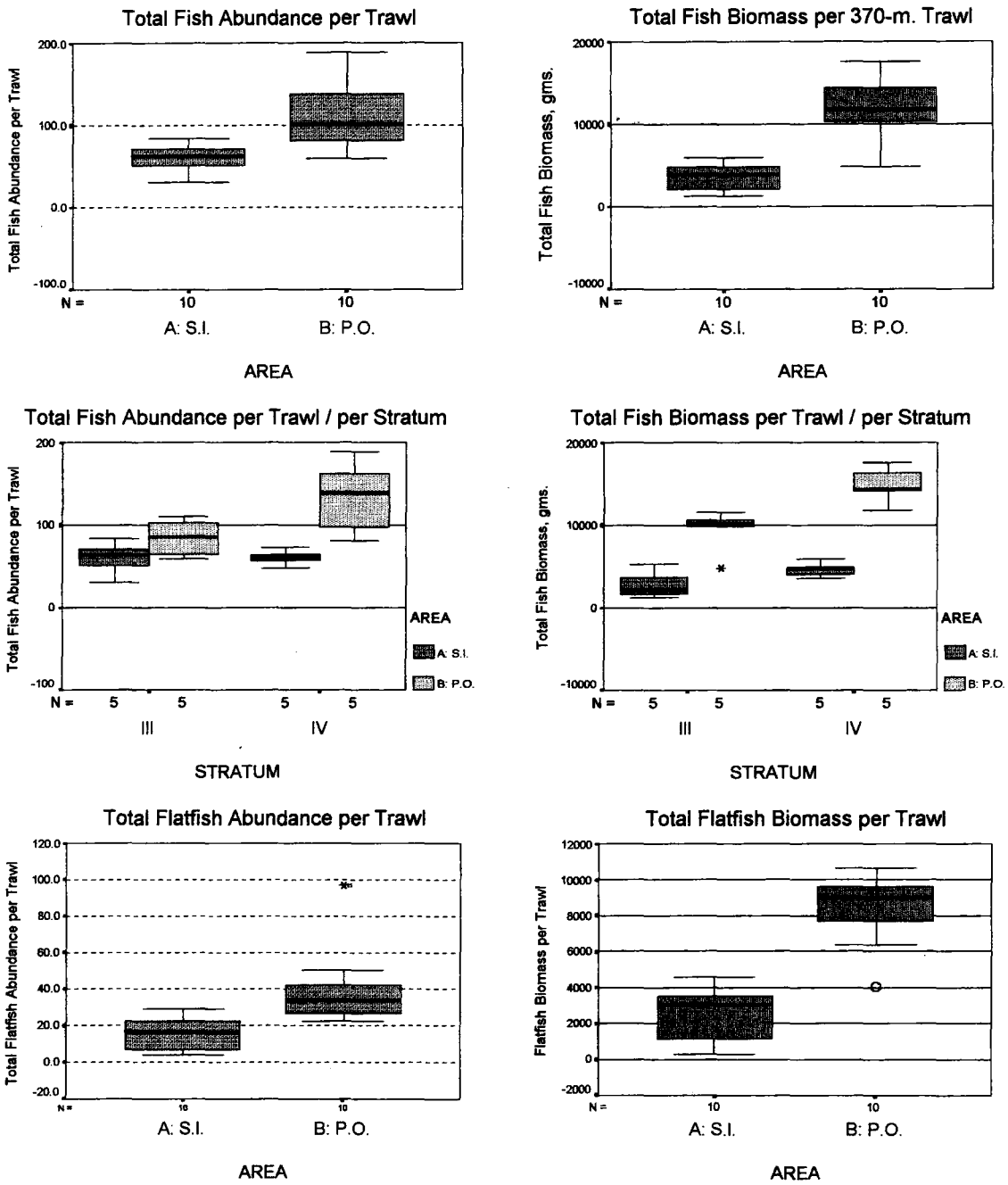

Figure 2. Comparisons of fish abundance and biomass metrics between the Sinclair Inlet (SI) test site and the Port Orchard (PO) reference site. Results were either combined for the two strata (n=10) or the strata were analyzed separately (n=5). Note the wider separation of the biomass data between the test and reference site compared to the abundance data. All fish trawls were 370 m long at 2.5 knots.

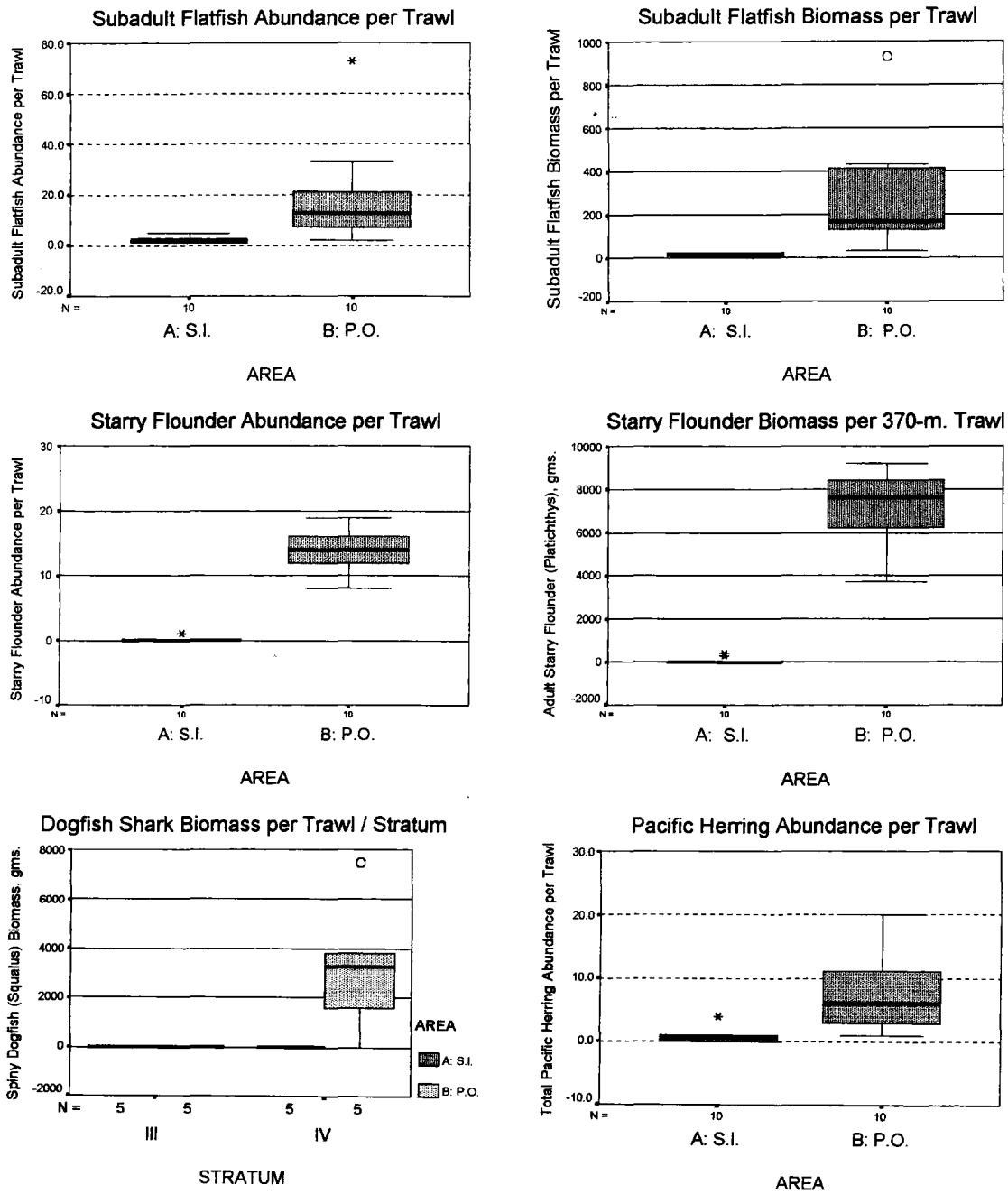

Figure 2 (cont.). Comparisons of fish abundance and biomass metrics between the Sinclair Inlet (SI) test site and the Port Orchard (PO) reference site. Subadult flatfish (<150 mm long), adult starry flounder, and Pacific herring were almost absent from the test site in Sinclair Inlet. Spiny Dogfish (*Squalus acanthias*) were not encountered in Sinclair Inlet, nor in stratum III of the reference area (PO). All fish trawls were 370 m in length at 2.5 knots.

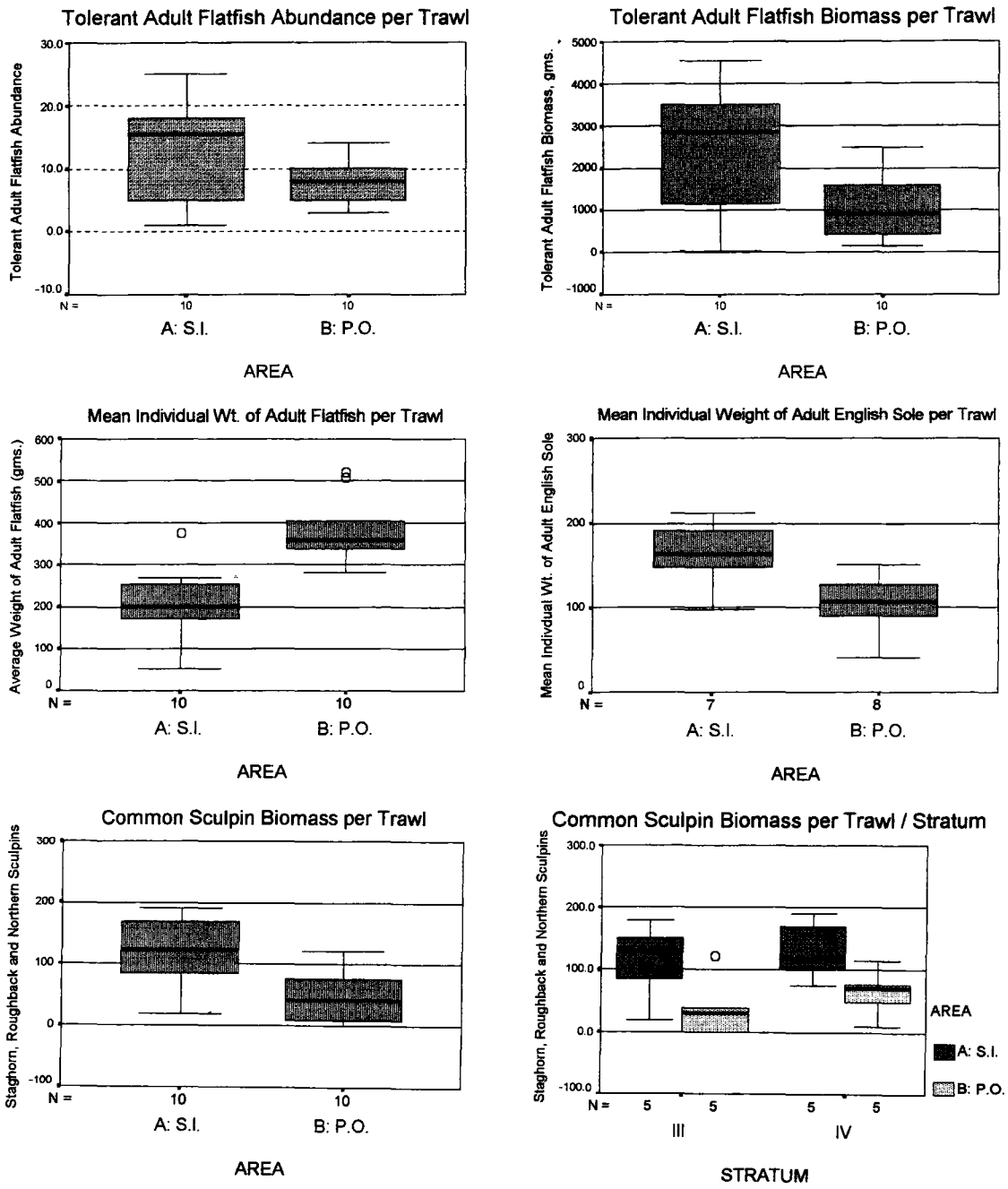

Figure 3. Some tolerant fish categories. Tolerant flatfish species (all flatfish except subadults and starry flounder) were numerically more abundant and more variable at the Sinclair Inlet test site. Although the mean individual weights of adult flatfish as a group was much higher at the Port Orchard (PO) Reference site (primarily because of starry flounder), the mean individual weight of adult (>150 mm) English sole was higher at the Sinclair Inlet (SI) test site. The common sculpins (primarily staghorn sculpins) seemed to flourish at the test site as was the case in the Hylebos and Thea Foss Waterways Superfund sites during the Phases I and II studies. All fish trawls were 370 m in length at 2.5 knots.

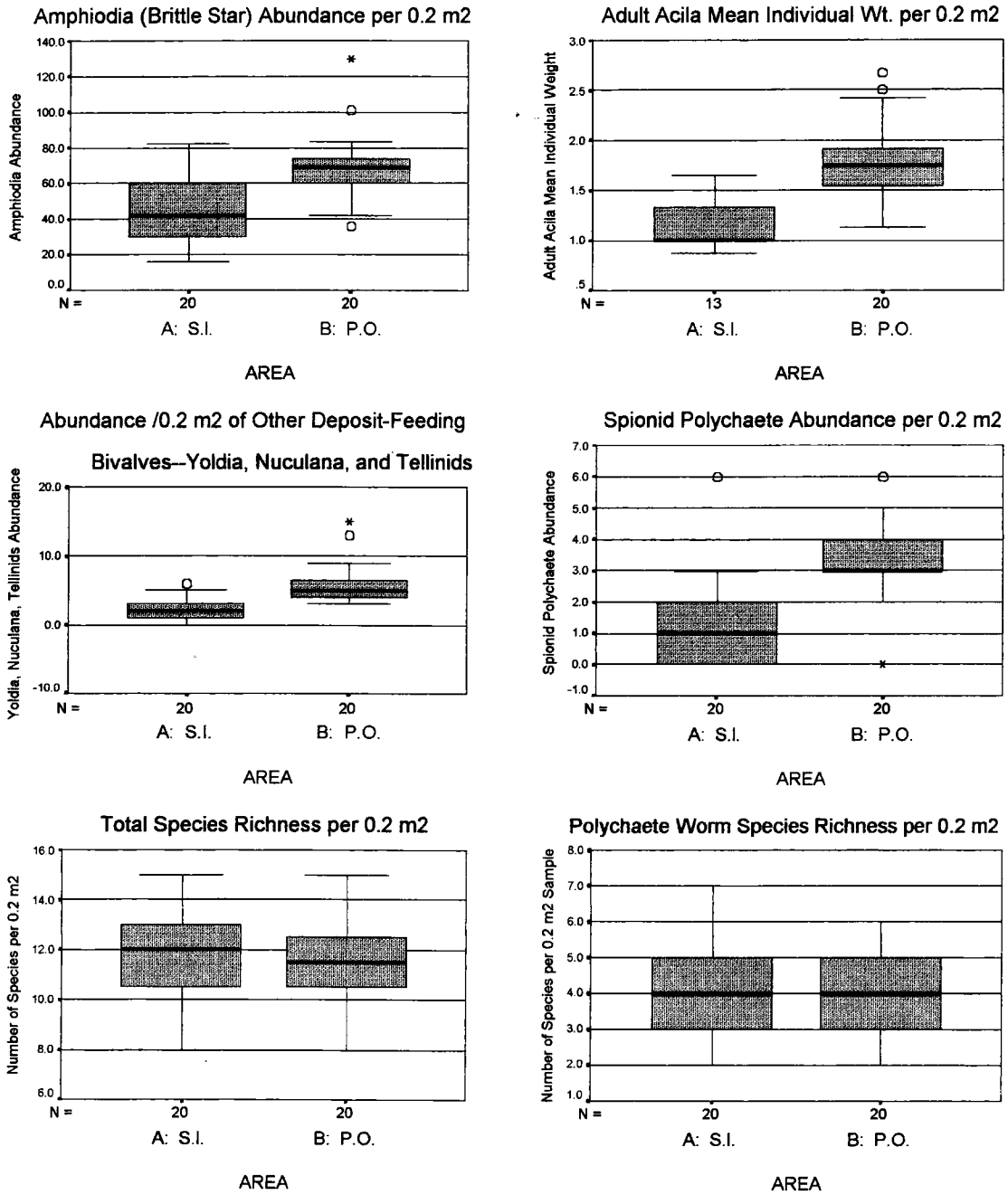

Figure 4. Some metrics tested for the macrobenthic infaunal assemblage in Phase III. Brittle star (*Amphiodia urtica*) abundance, adult nut clam (*Acila castrensis*) mean individual weights (adults and juveniles were weighed separately as groups), and the abundance of spionid polychaetes and other deposit-feeding bivalves appear to have some promise as useful metrics in separating the Sinclair Inlet test site from the Port Orchard reference site. The derived metrics of species richness, dominance and evenness were not useful at the level of the 4-mm screens. All samples were taken with a 0.2-m^2 van Veen sampler, sieved through 4-mm screens, and processed onboard.

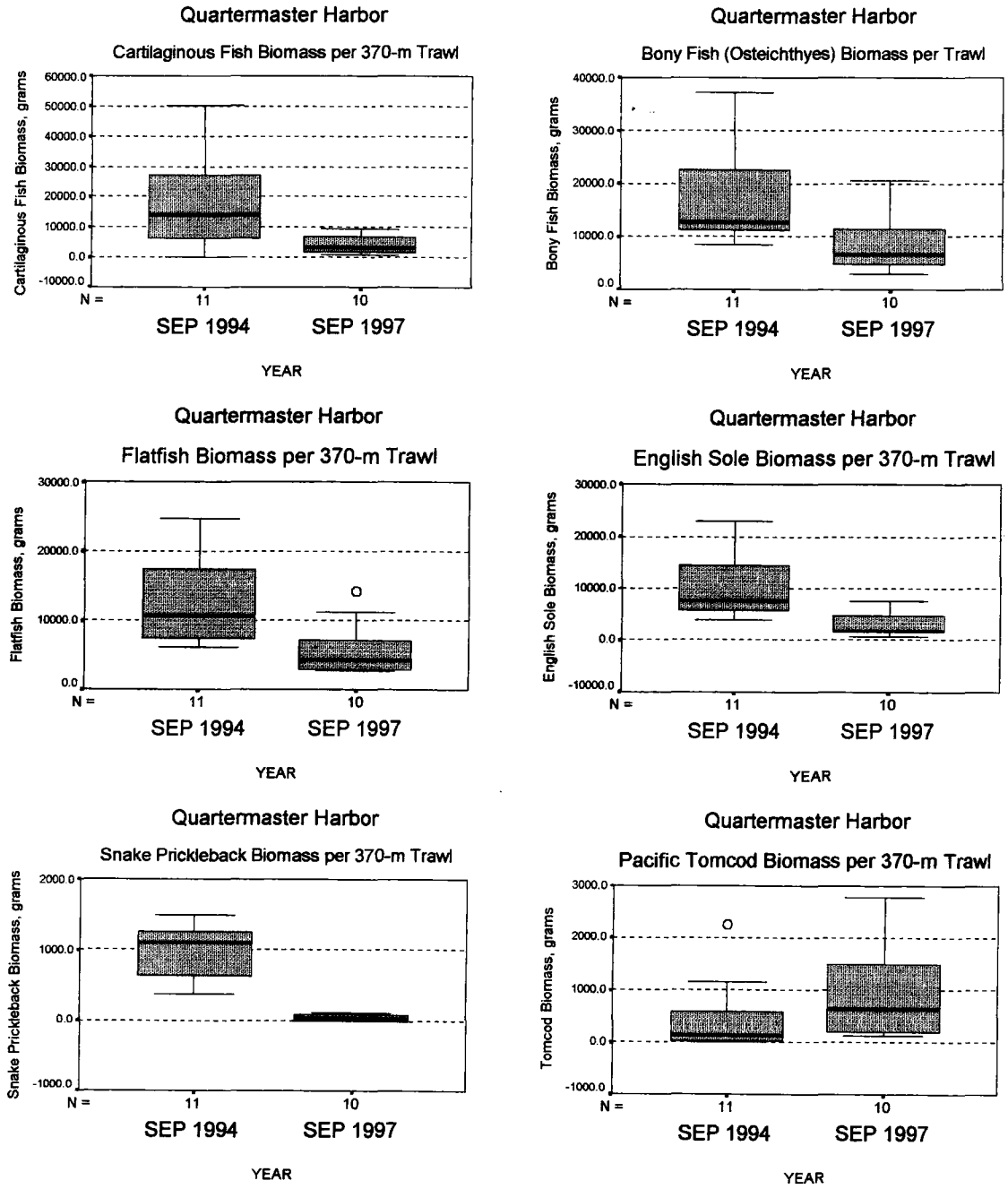

Figure 5. Comparisons of three-year, interannual variation in demersal fish biomass categories, September 1994 and September 1997, mid-Quartermaster Harbor. Most categories declined over the three-year period, although some categories showed no change (spiny dogfish, rock sole, flatfish mean individual weights), and a few actually showed a numeric increase (starry flounder, Pacific tomcod, and Pacific herring). This means that three-year-old demersal fish data cannot be used for comparisons to contemporary data.

Macrobenthos

The macrobenthic infaunal assemblage was sampled with a 0.2-m^2 van Veen sampler and screened through 4-mm mesh screens (Figure 4). Ten random replicate samples were taken per stratum for a total processed sample of 2.0 m^2. All retained invertebrates were processed onboard. Polychaete identification

was aided by the expert advice of Kathy Welch from WDOE/EILS. All animals were identified and counted, and larger species, mainly bivalves, were also weighed. Brittle stars (*Amphiodia*) were counted on the screens (bodies only). Ten to 15 samples per day could be collected and analyzed. Temperature, salinity, and sediment grain-size data were also assessed in each sample.

Potentially valuable metric variables (Figure 4) from the 4-mm mesh screens that were numerically **higher** at the Port Orchard reference sites include the following (remember that the mean size of most of these species is larger than for those retained on 1-mm screens):

- Brittle star (*Amphiodia*) abundance;
- Nut clam (*Acila castrensis*) biomass and mean individual weights;
- Other deposit-feeding bivalve abundance (*Yoldia*, *Nuculana*, and tellinids);
- Spionid polychaete abundance; and
- Capitellid polychaete abundance.

Potentially valuable metric variables from the 4-mm mesh screens that were numerically lower at the Port Orchard reference sites include the following:

- Chaetopterid polychaete abundance;
- Goniadid and glycerid polychaete abundance;
- Burrowing anemone (*Pachycerianthus*) abundance; and
- Ribbon worm (Nemertea) abundance.

Potential metric variables that showed no promise in discriminating between test and reference sites:

- All taxa-richness categories; and
- Polychaete total abundance.

Temporal Demersal Fish Variation in Quartermaster Harbor, September 1994 to September 1997

In order to study the kinds of temporal variation one might expect in demersal fish data collected over a three-year time span, 10 replicate trawls from strata III and IV from mid-September, 1997 were compared to the 10 replicate trawls taken in the same area using the same gear and boat during mid-September, 1994. No commercial fishing had taken place in Puget Sound during the three-year period. The results, summarized in Figure 5, include the following:

Declining Categories:

- Total numeric fish abundance and biomass in 1997 was <40% of that encountered in 1994.
- Flatfish abundance and biomass decreased by about 50%, with all species except starry flounder and rock sole showing dramatic declines. English Sole abundance declined by 67%.
- Cartilaginous fish abundance declined by 77%, all of which was represented by the spotted ratfish.
- Shiner surfperch (78%), staghorn sculpins (51%), and snake pricklebacks (94%) all displayed large numeric declines in abundance.

Increasing Categories:

- Both adult and subadult Pacific tomcod increased by more than 200%.
- Pacific herring displayed a 150% numeric increase.
- Starry flounder increased by <300%, whereas rock sole showed no change.

Discussion

The data from the 1997 sampling period (Phase III) definitely represents the best-paired comparison of test and reference data from the three phases of the Puget Sound biocriteria developmental research, with the data from Phases I and II both hindered by mismatches. The Hylebos Waterway test site in Phase I contained an abundance of woody debris not found in the Blair Waterway reference, which may have complicated the comparisons. The Quartermaster Harbor reference comparison to the Thea Foss Waterway, although showing comparable physical parameters in September, may indeed be of another class when physical parameters are sampled continuously or monthly. In Phase III, it was hoped to compare the test site, Sinclair Inlet, to two reference sites, upper Port Orchard and mid-Quartermaster Harbor. Although the physical parameters were well matched, the benthic infaunal community of Quartermaster Harbor obviously did not represent the same biological community as was encountered in Sinclair Inlet and Port Orchard. For this reason, the main emphasis was placed on the comparison of these last two areas, and the Quartermaster Harbor sampling was used primarily to study the temporal variation in the demersal fish community between September, 1994 and September, 1997. Of course all of these efforts provide valuable lessons for applying biocriteria to Puget Sound, which are summarized in Table 1. The predicted metric response to impairment is based on the history of the Puget Sound biocriteria research, with the Phase III study given highest priority, followed by Phase I and then Phase II. The recommendations for studying and incorporating data from the three biological assemblages follows:

Demersal Fish, 7.6-m Otter Trawl

The demersal fish community seems especially sensitive to environmental impairment in Puget Sound and can be easily and economically sampled with live, onboard processing. With the methods developed over 18 years of research trawling, up to eight trawls per day can be collected and processed with very little mortality. The added emphasis of separately processing adults and subadults of most species has added increased refinement to the evaluation and efficacy of the candidate metrics.

Demersal fish metrics that seem especially powerful for differentiating impaired conditions from reference, and whose response to environmental impairment is noted, include the following (Table 1):

Total fish biomass	reduced
Total flatfish biomass	reduced
Total adult flatfish mean individual weights	reduced
Total cartilaginous fish biomass	reduced
Starry flounder biomass	reduced
Pacific herring abundance and biomass	reduced
Common sculpin abundance and biomass	elevated
Tolerant fish categories (all flatfish except starry flounder, subadult shiner surfperch, subadult Pacific tomcod, subadult snake prickleback, staghorn sculpin, roughback sculpin, northern sculpin)	elevated or no significant difference

Demersal fish metrics that have good, but as yet unproved potential include the following:

Subadult flatfish abundance	reduced
Adult Pacific tomcod, adult shiner surfperch and adult snake prickleback abundance and biomass	reduced
Sensitive Category Index	reduced

Demersal fish metrics for which potential has been reduced by the Phase III sampling include:

- Mean individual weights of individual flatfish and gadid species (complicated by the presence/absence of competitors);
- Weight-length regressions (WAL) for adult flatfish species—the only correlations detected were to size class and not to site or stratum; and
- Derived metrics such as richness, dominance and evenness.

Demersal Fish Metrics over Time: QMH '94 vs. QMH '97

Although more cases of temporal variation need to be documented, the precipitous change in most metrics from two of the Quartermaster Harbor strata between September of 1994 and September of 1997 (Figure 5) does not bode well for anything but synoptic sampling of reference and test sites for this biological assemblage. The epibenthos (3-m beam trawl) were not sampled in 1997, so no conclusions can as yet be drawn concerning the temporal variation of this assemblage. Continued late-summer sampling of all the QMH strata are recommended to establish trends and more data on temporal variation.

Epibenthic Invertebrates and Small Fishes, 3-m Gunderson Beam Trawl

Although the epibenthos was not sampled in Phase III, the earlier phases provided a wealth of data and lessons. In Phase I, the best information came from the beam trawl, despite the difficulty of using the gear in a waterway with abundant wood debris. Future recommendations for sampling with this gear would include shortening up the beam trawl tows to 100 m in length and increasing the number of random replicate samples to five.

Epibenthic metrics from the beam trawl showing the greatest potential for differentiating impaired from reference conditions include (Table 1):

Sensitive fish categories (juvenile bay goby, juvenile blackbelly eelpout)	reduced
Total fish abundance	reduced
Total fish species richness	reduced
Subadult snake prickleback abundance	elevated
Staghorn sculpin and total sculpin abundance and biomass	elevated
Giant sea cucumber (*Parastichopus*) abundance	reduced
Total crustacean abundance and biomass	elevated
Cancer gracilis abundance and biomass	elevated
Sensitive Category Index	reduced

Macrobenthic Infauna on 4-mm Mesh Screens

The goal for the development of metrics for the macrobenthos was to increase the economy of the data derived from this biological assemblage to more closely match the data from the demersal fish and epibenthic assemblages. By increasing the screen mesh size (from 1.0 mm to 4.0 mm) as well as the sampler size (from 0.1 m^2 to 0.2 m^2) and the number of replicates (from 5 to 10), and then using onboard processing, the goal was to derive useful complimentary metrics at one-tenth the cost of metrics derived from 1.0-mm screens. The samples used for the macrobenthos need to be collected in any case for measurements of the physical environmental factors including sediment grain size, sediment temperature, and salinity of the overlying water. Future research recommendations for the development of the infaunal metrics would include the trial of screen mesh intermediate between the 4-mm and 1-mm screens.

Potentially valuable metric variables from the 4-mm mesh screens that were numerically higher at the Port Orchard reference sites include the following:

- Brittle star (*Amphiodia*) abundance;
- Nut clam (*Acila castrensis*) biomass and mean individual weights;
- Other deposit-feeding bivalve abundance (*Yoldia*, *Nuculana*, and tellinids);
- Spionid polychaete abundance; and
- Capitellid polychaete abundance.

Potentially valuable metric variables from the 4-mm mesh screens that were numerically lower at the Port Orchard reference sites include the following:

- Chaetopterid polychaete abundance;
- Goniadid and glycerid polychaete abundance;
- Burrowing anemone (*Pachycerianthus*) abundance; and
- Ribbon worm (Nemertea) abundance.

Summary

The three phases of the biocriteria/bioassessment developmental research have attempted to construct useful metrics derived from population patterns and health indices of three different marine biological assemblages. Each assemblage and sampling technique represents a different and complimentary assessment scale from the largest and most-mobile demersal fish scale (370-m trawls) to the smallest and least-mobile macrobenthic invertebrate scale (0.2-m^2). Random replicate sampling and the comparison of central tendencies to reference value benchmarks (the biocriteria) lies at the heart of the biocriteria/bioassessment methods. By scoring each metric based on its relative distance to the reference value benchmark and combining the scores into an index for each biological assemblage, it is hoped that both economy and ecological meaning can be restored to the assessment and cleanup of environmental impairment.

Aknowledgements

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Marine Benthic Invertebrate Communities Near King County's Wastewater Outfalls

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Introduction

Marine benthic communities near King County's wastewater outfalls were studied as part of King County's National Pollution Discharge Elimination System (NPDES) monitoring to determine if discharges from the wastewater treatment plants are affecting the surrounding benthos. Marine benthic communities are studied because they spend most of their lives in direct contact with the sediment, and therefore are useful indicators of sediment quality. Metal and organic pollutants contained in sediments and sediment pore water could be consumed or adsorbed by the benthos, resulting in unhealthy animals, stressed communities, and the potential passage of these pollutants through the food web to other organisms.

Communities can be analyzed and characterized in many different ways. One of the most common methods is by looking at community diversity. Diversity is a measure of the complexity of the community structure, and is increased or decreased by physical, chemical, and biological factors. High diversity is generally good, as it indicates a balanced, stable, responsive community. Low diversity occurs in an area where the community is dominated by a few species, such as in a stressed area of high pollution, large and frequent disturbances, or anoxic sediments. Diversity indices are commonly used because of their ease of calculation, but are also criticized because of their lack of detecting community changes due to one environmental factor (Cao et al., 1996) and because they assume a normal community distribution (Tetra Tech, 1985). Many multivariate and biotic indices have recently become popular, but they require inferences about important information such as the feeding strategies of many organisms. Calculating abundances of pollution tolerant and pollution sensitive species is another useful method for examining community differences and determining factors influencing community structure. *Capitella capitata* is a polychaete widely used as an indicator of polluted, anoxic, or organically enriched sediments (Pearson and Rosenberg, 1978). The amphipod *Rhepoxynius abronius* and ophiuroids (brittle stars) have been used as indicators of clean, undisturbed sediments (Comiskey et al., 1984).

Benthic communities in this study were examined by calculating several diversity indices, calculating abundances, and determining community compositions. Significant differences were determined using analysis of variance (ANOVA) tests. Possible physical, biological and chemical environmental factors structuring the communities were also investigated.

Methods

Sediment samples were collected at multiple sites near the sewage treatment plant outfalls biannually from 1988 to 1996. Stations LSKQ04 and KSRK02 were sampled biannually from 1988 to 1994 and will be two of the stations investigated in this study. Station locations were slightly changed in 1996, so stations AL172N and WP215N were compared with LSKQ04 and KSRK02. Stations LSKQ04 and AL172N are located north of the Alki outfall, while stations KSRK02 and WP215N are located just north of the West Point outfall. Data collected in 1990 was not used for this community analysis because replicate samples were not recorded in a usable format. The month of sample collection varied annually, but was always either late summer or early fall.

Samples for benthic community analysis were collected with a 0.1-m^2 van Veen grab sampler. Five replicate samples were taken at each station in all years. Concurrent samples utilizing only the top 2 cm of sediment were collected for sediment grain-size distributions and total organic carbon (TOC) concentrations. Sediment collected for benthic community analysis was passed through a 1-mm sieve,

and all retained organisms were collected, stored in fixatives, and stored for later taxonomic identification and enumeration. All animals were identified to the lowest possible taxonomic level, usually species, by taxonomic experts. After identification, the data set was reviewed and incidental catches, pelagic species, and colonial species were removed. Diversity indices and abundances were calculated with Excel 4.0 spreadsheets, and statistical analyses were performed with SPSS statistical software.

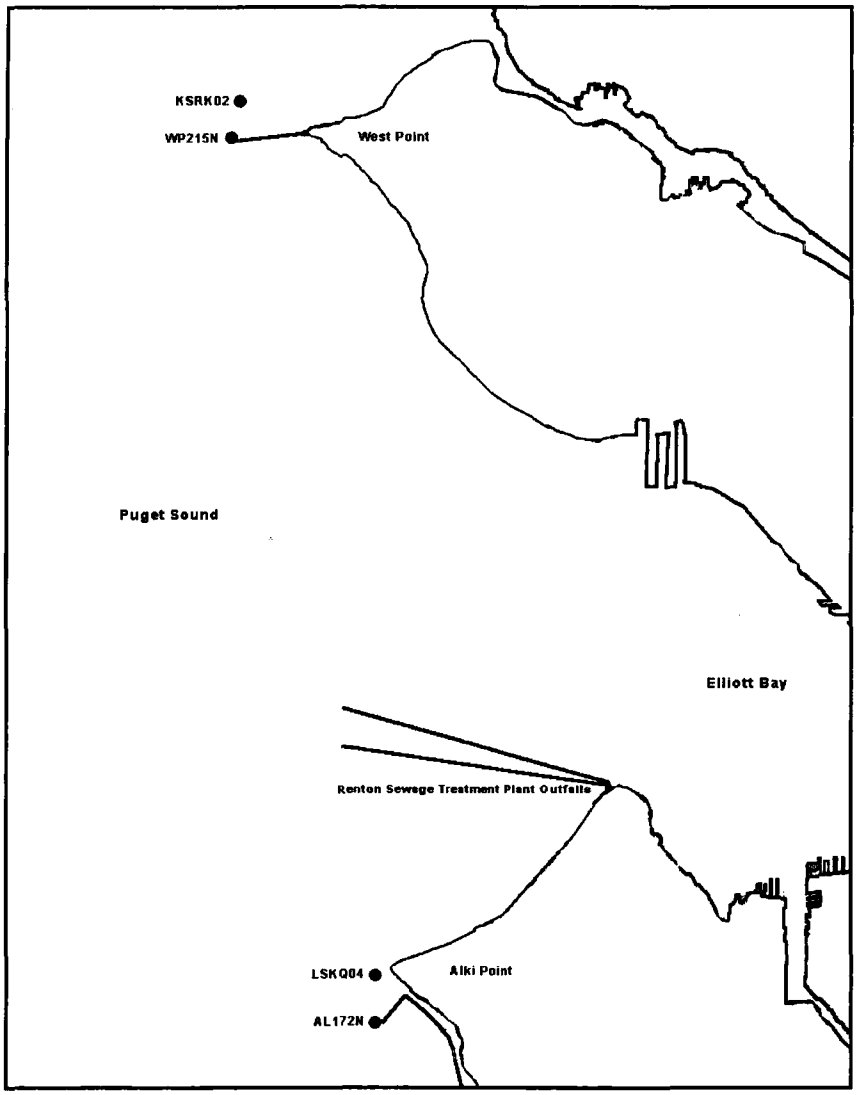


Figure 1. Map of all sample locations in King County, Washington.

Results

Diversity Indices

Three diversity indices were calculated to examine community changes over time for this study. The Shannon-Wiener diversity index (Valiela, 1984) was calculated with the following equation.

$$H' = \sum_{i=1}^{s} P_i \log_2 P_i$$

Where H' = Shannon-Wiener diversity index
P_i = Number of individuals in the ith species
S = Number of species

Values ranged from 3.51 to 6.2 and averages are presented in Table 1. No significant differences were calculated at station LSKQ04, but the benthic community at station KSRK02 in 1994 was significantly less diverse than all other communities at that station.

Pielou's evenness index (Valiela, 1984) was also calculated for this study using the equation:

$$J=H'/\log_2 S$$

Where J = Pielou's evenness index
H′= Shannon-Wiener diversity index
S = Number of species

Values for this index ranged from 0.42 to 0.89 and averages are presented in Table 1. The only significant differences discovered with this index were at both stations in 1994. The evenness index indicated that these two communities were less diverse than all others.

The final index used for community comparisons was Swartz's dominance index, which measures the number of species whose combined abundance comprises 75% of the total sample abundance. Values less than 5 usually indicate a stressed community (PTI, 1993). Average values ranged from 17.8 to 40.6 and are shown in Table 1. No differences were detected based on Swartz's index at station LSKQ04, but at station KSRK02 communities in 1988 and 1994 were significantly less diverse than communities in 1992 and 1996.

Table 1. Summary of diversity indices, abundances, and physical characteristics of all stations in all years. All indices and abundances are averages of five replicate samples.

	1988		1992		1994		1996	
	KSRK02	LSKQ04	KSRK02	LSKQ04	KSRK02	LSKQ04	WP215N	AL172N
Mean Shannon-Wiener	**5.02**	**5.50**	**5.86**	**5.85**	**4.35**	**5.69**	**5.89**	**5.60**
standard deviation	0.90	0.78	0.37	0.20	0.61	0.32	0.28	0.19
Mean Evenness	**0.85**	**0.86**	**0.87**	**0.81**	**0.46**	**0.64**	**0.88**	**0.87**
standard deviation	0.06	0.04	0.02	0.06	0.09	0.04	0.04	0.02
Mean Swartz's	**23.60**	**29.40**	**40.60**	**39.60**	**17.80**	**33.60**	**38.40**	**29.40**
standard deviation	9.24	10.41	10.01	5.98	6.26	3.65	4.28	4.51
Mean Total Abundance	**229**	**462**	**415**	**1255**	**835**	**502**	**462**	**342**
standard deviation	84	292	172	701	313	108	196	79
Mean # Species	**63**	**93**	**110**	**159**	**91**	**109**	**108**	**88**
standard deviation	23	40	26	47	15	14	22	9
Total Organic Carbon (mg/kg)	3800	1600	2100	4400	9840	4370	1310	1500
Depth (m)	89 m	35 m	95 m	66 m	95m	63m	78 m	50 m
Grain Size—% gravel	0.31	9.23	0.00	5.44	2.60	6.10	0.70	1.00
% sand	88.45	50.01	92.08	87.17	78.90	81.30	91.40	93.20
% silt	8.43	24.93	4.55	2.09	9.10	7.10	5.60	5.60
% clay	2.81	15.83	3.37	5.30	9.10	5.80	0.00	0.00

Abundances

Total average abundances ranged from 229 to 1255 and are listed in Table 1. Station KSRK02 in 1994 and station LSKQ04 in 1992 both had significantly higher abundances than all other communities. Averaged total numbers of species are also presented for each station in Table 1, and ranged from 63 to 159. The total number of species was significantly higher at LSKQ04 in 1992, but significantly lower in 1988 at station KSRK02. Abundances of the five numerically dominant species at each station are listed in Table 2. The types of numerically dominant species varied among years and between sites. The percent of organisms in each of the major taxonomic groups was calculated for each site and are presented in Figures 2 and 3. Except for station KSRK02 in 1994, the stations had very similar community compositions among years. This distribution among major taxonomic groups remained similar even though the dominant species varied among years.

Table 2. Abundances of the five numerically dominant species at each station for each year. Major taxonomic group and percent of the total sample abundance is given for each species.

Year	Station	Dominant Species	Taxonomic Group	Average Number of Individuals	Percent of Total Abundance (%)
1988	KSRK02	*Prionospio steenstrupi*	Polychaetea	36.2	15.8
		Spiophanes bombyx	Polychaetea	14	6.1
		Euphilomedes carcharodonta	Crustacea	11	4.8
		Macoma yoldiformis	Mollusca	6.6	2.9
		Polycirrus sp.	Polychaetea	6.2	2.7
1992	KSRK02	*Ampharete acutifrons*	Polychaetea	53.2	12.8
		Pectinaria californiensis	Polychaetea	15.4	3.7
		Proclea graffii	Polychaetea	14.6	3.5
		Paraprionospio pinnata	Polychaetea	14.2	3.4
		Bittium attenuatum	Mollusca	11.4	2.7
1994	KSRK02	*Golfingia minuta*	Sipuncula	331.4	39.7
		Erichthonius sp.	Crustacea	28.8	3.5
		Polydora sp.	Polychaetea	26.4	3.2
		Caprella mendax	Crustacea	21.2	2.5
		Megacrenella columbiana	Mollusca	17.6	2.1
1996	WP215N	*Hiatella arctica*	Mollusca	50.2	10.9
		Neosabellaria cementarium	Polychaetea	31.4	6.8
		Pholoides asperus	Polychaetea	13.4	2.9
		Byblis millsi	Crustacea	12.2	2.6
		Dipolydora akaina	Polychaeta	11.8	2.6
1988	LSKQ04	*Euphilomedes carcharodonta*	Crustacea	34.2	7.4
		Tritella pilimana	Mollusca	35.75	7.7
		Pholoides aspera	Polychaetea	18.8	4.1
		Prionospio steenstrupi	Polychaetea	14	3.0
		Spiochaetopterus costarum	Polychaetea	13.8	3.0
1992	LSKQ04	*Pholoides aspera*	Polychaetea	177.2	14.1
		Phyllochaetopterus prolifica	Polychaetea	105	8.4
		Phoronopsis harmeri	Phoronida	42.8	3.4
		Ericthonius sp.	Crustacea	32.6	2.6
		Heteronemertea	Nemertea	28	2.2
1994	LSKQ04	*Caprella mendax*	Crustacea	40.6	8.1
		Peisidice aspera	Polychaetea	29	5.8
		Phyllochaetopterus prolifica	Polychaetea	28.8	5.7
		Erichthonius sp.	Crustacea	26.6	5.3
		Sabellidae	Polychaetea	24.6	4.9
1996	AL172N	*Tritella pilmana*	Crustacea	32.4	9.5
		Aoroides sp.	Crustacea	27.4	8.0
		Cucumaria piperata	Holothuroidea	19.6	5.7
		Caprella mendax	Crustacea	13.2	3.9
		Lumbrineris californiensis	Polychaeta	13	3.8

Figure 2. West Point

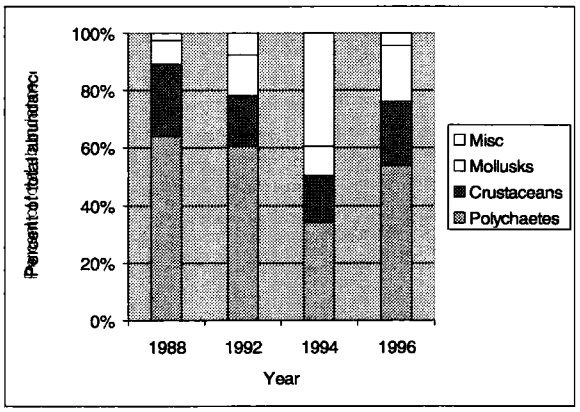
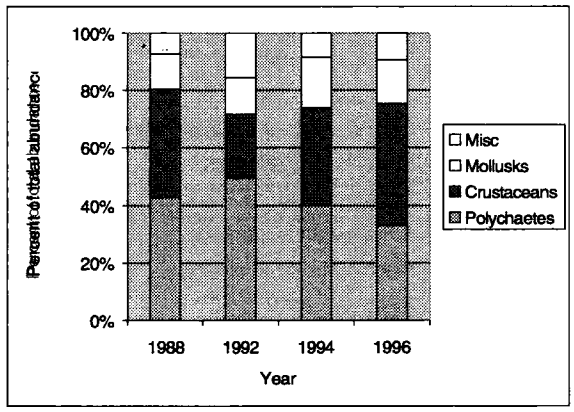


Figure 3. Alki Point



Figures 2 and 3. Percentage of organisms in each major taxonomic group at stations KSRK02 (left) and LSKQ04 (right). Percent of organisms based on averages of five replicates.

Discussion

Stations KSRK02 and WP215N, West Point

All diversity indices and total abundances indicated that stations KSRK02 and WP215N in 1994 were less diverse but had more individual organisms than all other years. This is due to the large number of sipunculan worms, *Golfingia minuta*, recovered in 1994. These surface-detritus feeders are only a few mm long and like to occupy vacant foraminifera tests (Barnes, 1980; Kozloff, 1990). *Golfingia minuta* could be present in high abundances because of patchy distributions of the animal, larval recruitment patterns, food availability, or many other physical and biological factors. Variability of station location because of different location methods (Loran and GPS) is another possible source of community variation. Future sampling should investigate this species to track further population fluctuations and explore possible explanations.

No significant correlation between diversity indices and physical factors were detected at the West Point stations. However, a weak correlation was observed between all diversity indices and total organic carbon values, indicating that this is a possible factor controlling and structuring the communities. Not including the stations in 1994, the numerically dominant species varied among years, yet the percent of organisms in each of the major taxonomic groups remained very similar. This could indicate that the overall environment is relatively stable and maintains a constant community composition from year to year, yet small variations produce different numerically dominant species. These variations could include larval recruitment, food type and amount, species interactions, water temperature, sediment grain size, dissolved oxygen concentrations, and variability of station location. *Capitella capitata*, a pollution-tolerant polychaete worm, was not recovered at this station in any year. Conversely, Ophiuroids (brittle stars) are considered a pollution-sensitive species and were recovered at this station in all years. This indicates that the environment near the wastewater outfall at West Point is unpolluted enough to support a pollution-sensitive invertebrate.

Stations LSKQ04 and AL172N, Alki Point

Total abundance and number of species at stations LSKQ04 and AL172N in 1992 were significantly higher than in all other years. However, no differences were identified among diversity indices. This indicates that the communities are stable, yet responding to possible variations in food availability, larval recruitment, total organic carbon concentrations, and sampling station location. Abundances also could have been higher because the samples in 1992 were collected in late August, and in all other years samples were collected from mid-September to October.

A weak correlation was seen at this station between diversity values and total organic carbon, indicating that total organic carbon may be a factor structuring the benthic communities. The numerically dominant species varied among years, but the percent of organisms in each of the major taxonomic groups remained quite similar. This is the same situation observed at the West Point stations, and the same possible explanation applies here. The occurrence of pollution-tolerant and pollution-sensitive species, *C. capitata* and ophiuroids, was the same as at the West Point stations, and the same possible explanations also apply here.

Conclusions

Total organic carbon concentrations may be a factor structuring the benthic communities, because stations displayed a weak correlation of higher diversity values with decreasing total organic carbon. Factors structuring communities may be easier to detect with a greater number and a greater diversity of sampling locations. Other possible controlling factors include sediment grain-size distributions and dissolved oxygen concentrations.

Future studies would be enhanced by the collection of a reference site away from the sewage outfalls. This would allow for effects from the treatment plant outfalls to be determined more effectively. Suitable reference sites are difficult to find because variations in physical environmental parameters, sediment chemistry, natural fauna interactions, and seasonal conditions can result in very different benthic communities. Care should be taken when selecting a reference site; in fact, several references may need to be sampled to accurately compare to the study sites.

Based on the information gathered in this study, the benthic communities near King County's wastewater outfalls are probably not affected negatively by wastewater discharges, because the communities do not show dramatic changes in diversities or abundances over time. This can not be determined conclusively from this study, since only one station was sampled near the treatment plant outfalls, so effects around the outfall pipe could not be determined. Future benthic studies will utilize a very different station arrangement, and will allow gradient effects away from the outfalls to be investigated. Continued monitoring of these communities will remain a part of the NPDES permit, but monitoring is also essential to track long-term changes, to determine the health of the communities, and to further investigate which factors act to structure and control the communities.

Acknowledgments

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The Distribution and Structure of Soft-Bottom Macrobenthos in Puget Sound in Relation to Natural and Anthropogenic Factors[i]

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Introduction

The Marine Sediment Monitoring Program (MSMP), a component of the Puget Sound Ambient Monitoring Program (PSAMP), was established in 1989 to measure sediment quality conditions throughout the Puget Sound region (Puget Sound, Hood Canal, the Strait of Georgia, and the Strait of Juan de Fuca). The program focuses on the Triad approach for sediment monitoring (Chapman and Long, 1983). The Triad integrates sediment chemistry, toxicity, and benthic infauna in determining sediment quality.

The MSMP has focused on ambient conditions away from point sources of pollution. Results from the first seven years of monitoring data indicated that sediment contamination at most sampling stations was low or absent (Llansó et al., 1998). Only at some specific areas associated with industrial or urban centers did sediments show moderate chemical concentrations. With few exceptions, these concentrations were below Washington State Sediment Quality Criteria. Other state and federal programs in Puget Sound are monitoring conditions near sources of pollution where sediment contamination is substantial. These programs have the need for the identification of reference conditions to which data from polluted sites can be compared.

The objective of the present study is to characterize benthic macro-invertebrate communities in non-degraded habitats of Puget Sound. Once the characteristics of these communities are known, reference conditions and criteria can be established to distinguish degraded from non-degraded habitats. Also, of interest is the identification of potential natural stresses that may structure benthic communities in Puget Sound and which may constitute confounding factors in pollution monitoring efforts.

Methods

Benthic organisms were sampled in March–April 1989–1993 at 76 monitoring stations located throughout Puget Sound, Hood Canal, and the Straits of Georgia and Juan de Fuca (Figures 1–2). Two types of stations were established: core stations, sampled once every year; and rotating stations, sampled once every three years in a rotating cycle between the north, central, and south Puget Sound regions.[ii]

Sampling at each station consisted of five van Veen sediment grabs (0.1 m^2). The contents were washed through a 1.0-mm mesh screen using running seawater. The organisms were preserved in 10% buffered formalin in seawater, sorted and identified to species. Sediment contaminants (not presented here), total organic carbon, total sulfide, and grain size were measured from the top 2 cm of paired samples. See Llansó et al. (1998) for details on sample collection and analytical procedures.

The data files used to describe community structure in Puget Sound were first standardized to ensure common species nomenclature. Incidental and epifaunal organisms were eliminated from the data. To discern patterns in species abundance and composition, Margalef's Species Richness (SR) and Pielou's Evenness (J') were computed (Margalef, 1958; Pielou, 1966). The indices were calculated on composite samples, i.e., using the cumulative number of species in five samples. For each taxon and station, records with more than one level of identification were removed from the data files, leaving records with the lowest level of identification.

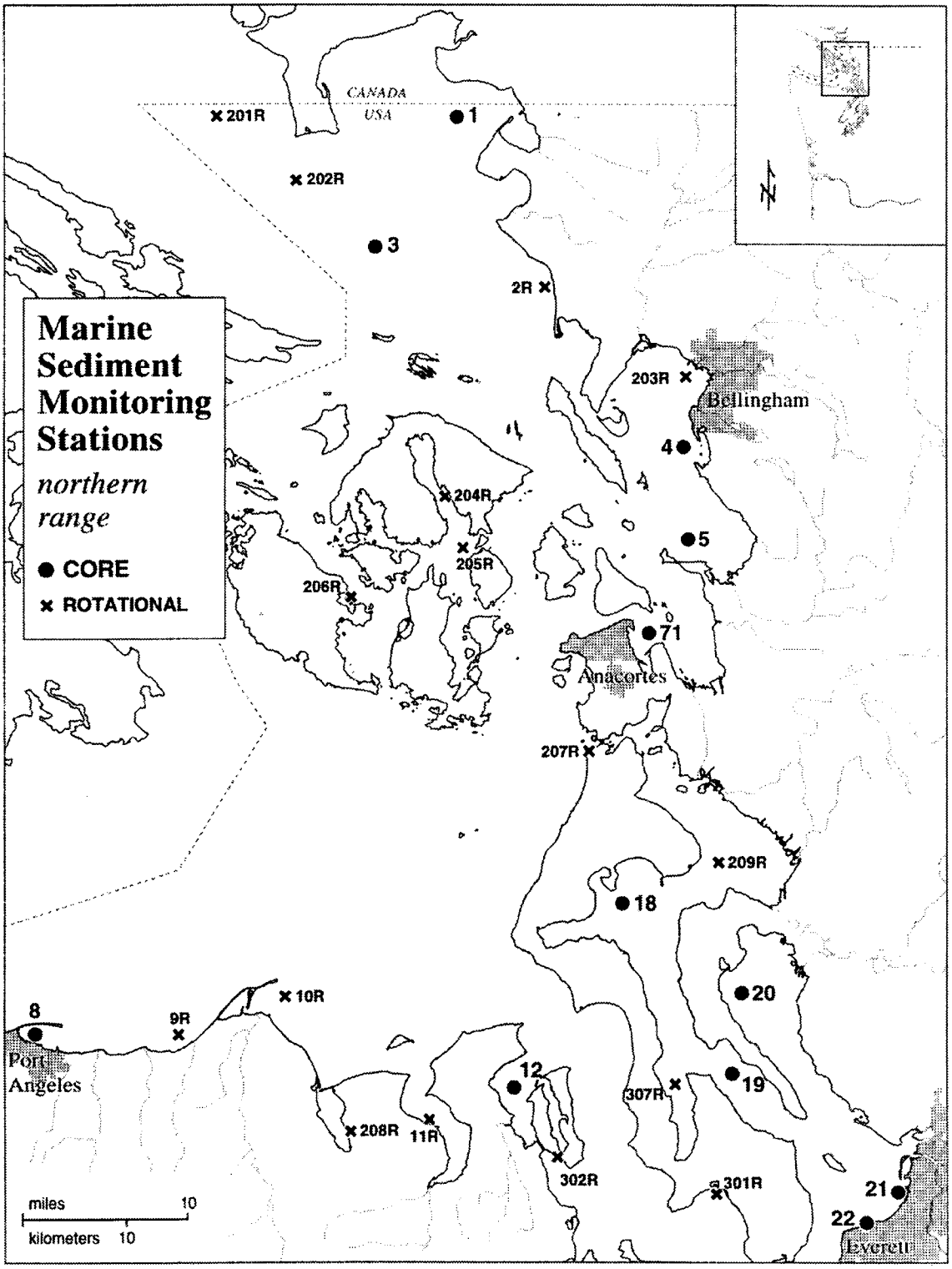

Figure 1. Map of station locations, northern range.

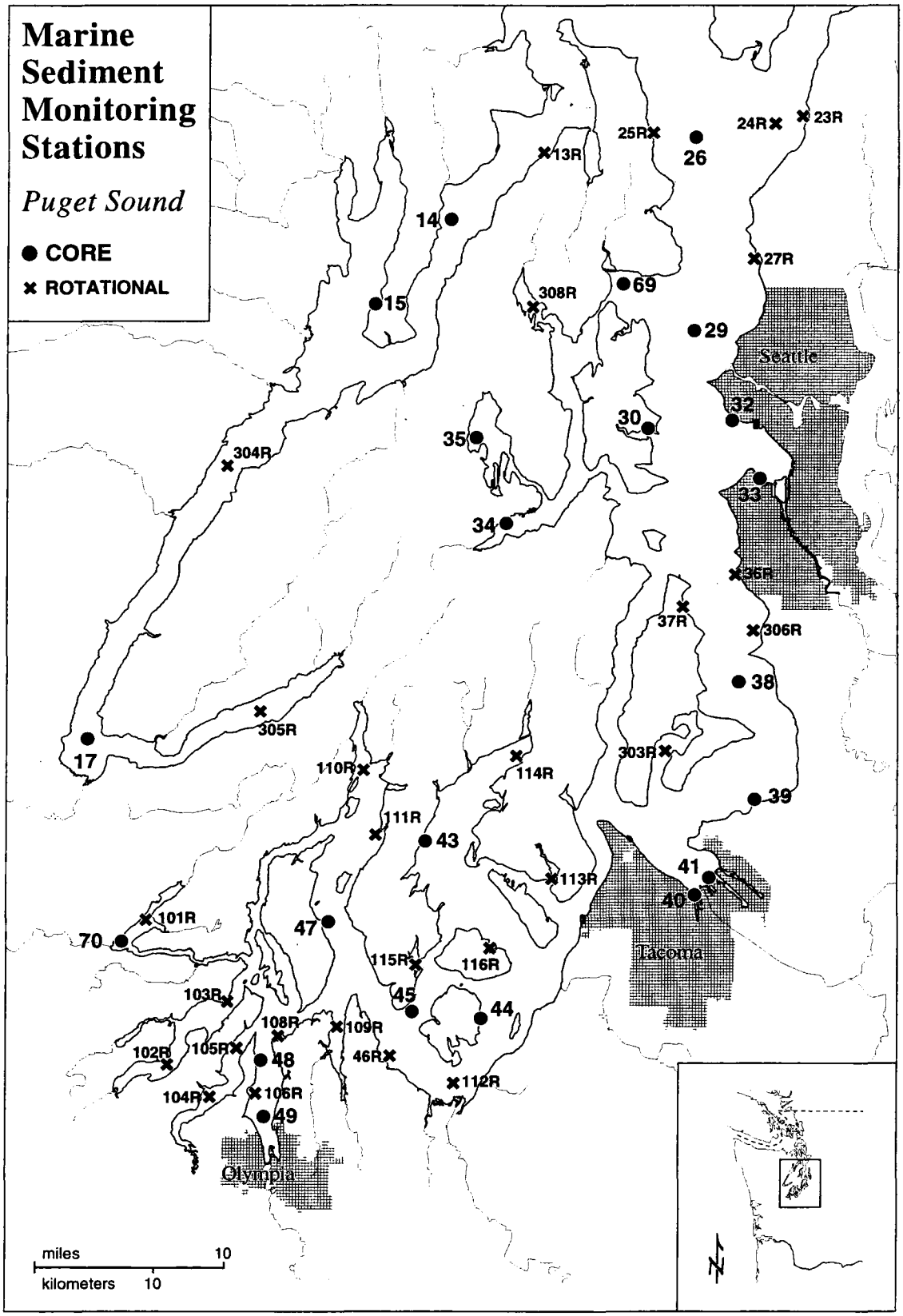

Figure 2. Map of station locations, southern range.

Spatial trends in species distributions were analyzed using numerical classification. Forty-one to 48 stations for each of five years were analyzed using the computer program COMPAH (Eugene Gallagher, Environmental Science Program, University of Massachusetts, Boston, MA). Both normal (by station) and inverse (by species) classifications were produced. The Canberra metric coefficient (Lance and Williams, 1966) and Group Average method (Sneath and Sokal, 1973) were used. Data were transformed to log (x+1).

In cluster analysis, and for each taxon and year, records with more than one level of identification were treated according to a "40% rule." If the abundance at a higher level of identification (e.g., genus) was less than 40% of the combined abundance of this and the next lower level (e.g., species), the lower level of identification was kept in the analysis and the higher level removed. Otherwise, the lower level of identification was merged to the higher level. In addition, taxa occurring below 1% of the total station abundance at all stations were eliminated from the analysis.

Using this last procedure, 63–66% of the taxa were eliminated from the analysis. These taxa, however, represented only 3–5% of the total abundance, and many were sampled infrequently in Puget Sound.

Also, analysis of station by species coincidence tables ("nodal analysis," not presented here) was used to relate the groups derived from normal and inverse classifications (Williams and Lambert, 1961; Boesch, 1977). Benthic measures were summarized and dominant species ranked for each of four categories of stations identified in the cluster analysis.

Results

Sediment Characteristics

Sediments sampled in Puget Sound were classified according to the proportion of sand, silt, and clay. The ranges used to classify the sediments were based on the grouping of stations in the classification analysis (see below). Three classes of sediments were distinct in the analysis: sands, >62% sand and low amounts of clay (<13%); mixed, 20–68% sand and up to 23% clay; and clays, typically ≤20% sand and higher amounts of clay (20–55%).

These three classes of sediments did not have sharp boundaries, but overlapped at both ends of their ranges. For example, some stations with a proportion of clay in the range 20–23% could be classified either as mixed or as clay. These stations, however, were primarily associated with either clay or mixed-type stations in the dendogram depending on their relative proportions of sand, silt, and clay.

Total organic carbon (TOC) ranged from 0.1–4.0%. Most sandy (98%) and mixed (82%) sediments had low TOC concentrations (≤1.5%). High TOC concentrations (>2.5%) were measured at stations where wood from log storage operations has accumulated in sediments, and at inlet ends in south Puget Sound.

Total sulfide concentrations >100 mg/kg were measured in some terminal inlets and semi-enclosed bays, or in areas associated with large freshwater plumes. In all these areas, density stratification is likely to restrict mixing of the water column, and hence, replenishment of dissolved oxygen (DO) to bottom waters.

Diversity

Species Richness (SR) remained relatively constant across years for most stations. Rankings for SR values across years were highly concordant (Kendall coefficient of concordance). Some stations (Table 1) had consistently low species richness (SR<7.0). These stations also exhibited benthic abundance that was significantly lower (ANOVA, $p<0.05$) than stations elsewhere.

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[i] This paper is based on a poster presentation, and represents a partial summary of a more detailed monitoring report in preparation.

[ii] Station locations provided upon request.

Table 1. Puget Sound stations with Margalef's Species Richness values below 7.0 by year, in rank order from low to high. The number of species at these stations was generally below 50, which represents 30% of the species recorded at the station with the highest species richness in Puget Sound. Note that the same core stations (sampled annually and designated with a number <100) appear in the list for most years. Also, the same rotating stations (sampled on a three-year rotation and designated with a number >100 and the letter "R") in south Puget Sound (100R-series) appear in the list in 1990 and 1993.

1989		1990		1991		1992		1993	
49	Inner Budd Inlet	3	Strait of Georgia	208R	Sequim Bay	305R	Lynch Cove	110R	Inner Case Inlet
17	S. Hood Canal	102R	Inner Totten Inlet	17	S. Hood Canal	17	S. Hood Canal	1	Semiahmoo Bay
1	Semiahmoo Bay	49	Inner Budd Inlet	70	Oakland Bay	307R	Holmes Harbor	104R	Inner Eld Inlet
		17	S. Hood Canal	204R	East Sound	70	Oakland Bay	17	S. Hood Canal
		106R	Mid Budd Inlet	49	Inner Budd Inlet	49	Inner Budd Inlet	114R	Henderson Bay
		104R	Inner Eld Inlet	1	Semiahmoo Bay	304R	Tekiu Point	49	Inner Budd Inlet
		1	Semiahmoo Bay	9R	Green Point	1	Semiahmoo Bay	102R	Inner Totten Inlet
		110R	Inner Case Inlet	3	Strait of Georgia	38	Point Pully	48	Outer Budd Inlet
		109R	Henderson Inlet	48	Outer Budd Inlet	48	Outer Budd Inlet	106R	Mid Budd Inlet
		114R	Henderson Bay			3	Strait of Georgia	109R	Henderson Inlet
		101R	N. Oakland					3	Strait of Georgia
		70	Oakland Bay					101R	N. Oakland Bay
		48	Outer Budd Inlet					38	Point Pully
								70	Oakland Bay

Stations with low evenness (J'<0.5), or showing fluctuations in J' values >0.15, reflected the numerical dominance of typically 20 species of benthic organisms plus the Phoronida (Table 2). Some of these species respond to organic enrichment, and because of opportunistic life-history strategies, may show large increases or decreases in abundance. The numerical dominance of these species at some locations may provide information about natural or human-related organic inputs to Puget Sound. One such species, the cirratulid polychaete *Aphelochaeta* sp., is discussed below in this context.

Table 2. Numerically dominant species in Puget Sound responsible for low evenness (J'<0.50) or fluctuations in evenness at the listed stations. A= Amphipoda, B= Bivalvia, C= Cumacea, D= Decapoda, E= Echinodermata, O= Ostracoda, P= Polychaeta, S= Sipuncula.

Species	Station
Amphiodia urtica-periercta (E)	1 Semiahmoo Bay, 35 Dyes Inlet
Aphelochaeta sp. (P)	8 Port Angeles, 30 Eagle Harbor, 35 Dyes Inlet, 41 Commencement Bay
Axinopsida serricata (B)	17 S. Hood Canal, 18 Oak Harbor, 41 Commencement Bay
Eudorella pacifica (C)	35 Dyes Inlet, 48 Outer Budd Inlet
Euphilomedes carcharodonta (O)	13R N. Hood Canal, 25R W. Central Basin
Macoma calcarea (B)	3 Strait of Georgia
Macoma carlottensis (B)	24R E. Central Basin, 29 Shilshole, 38 Point Pully
Macoma nasuta (B)	101R N. Oakland Bay
Nephtys cornuta (P)	102R Inner Totten Inlet, 208R Sequim Bay
Paraprionospio pinnata (P)	49 Inner Budd Inlet, 104R Inner Eld Inlet, 305R Lynch Cove
Pectinaria californiensis (P)	19 Saratoga Passage
Phoronida	15 Dabob Bay, 18 Oak Harbor
Phyllochaetopterus prolifica (P)	34 Sinclair Inlet, 35 Dyes Inlet
Pinnixa schmitti (D)	30 Eagle Harbor, 35 Dyes Inlet
Protomedeia grandimana (A)	1 Semiahmoo Bay
Psephidia lordi (B)	13R N. Hood Canal, 25R W. Central Basin, 101R N. Oakland Bay
Spiochaetopterus costarum (P)	18 Oak Harbor
Spiophanes berkeleyorum (P)	18 Oak Harbor
Spiophanes bombyx (P)	9R Green Point, 25R W. Central Basin
Thysanocardia nigra (S)	201R Roberts Bank
Yoldia sp. (B)	3 Strait of Georgia

On average, sand substrates supported higher number of species and abundance than clay substrates, with deep clay stations having the lowest abundance (Table 3).

Table 3. Abundance (mean number of individuals per 0.1 m^2 grab) and total number of species (five composite 0.1 m^2 grabs) of macrobenthos in Puget Sound. Numbers are averages (±SD) of stations grouped by sediment type over five years (1989–1993) of sampling.

	Sediment Type			
	Sand	Mixed	Clay	Deep Clay
Abundance	527.4 (±245.8)	411.9 (±223.2)	331.3 (±216.7)	189.3 (±124.6)
Number of Species	118.1 (±28.1)	83.0 (±21.2)	53.4 (±18.4)	52.4 (±12.0)

Similarities Among Stations

Classification analyses of stations are illustrated here for two years (Figures 3–4). The results from these analyses showed consistent patterns of spatial variation. These patterns could be explained primarily on the basis of differences in substrate composition and water depth, and secondarily on the basis of differences in species composition between north and south Puget Sound. Sandy stations were separated from clay stations, and generally from mixed stations.

Deep (80–200 m) clay stations formed a distinct group, regardless of location in Puget Sound. Shallow (≤20 m) clay stations were separated into north and south Puget Sound groups. A group of inlet end stations in south Puget Sound was distinct, especially for the two years for which rotating stations were sampled in south Puget Sound. These clusters are identified in bold in Figures 3–4.

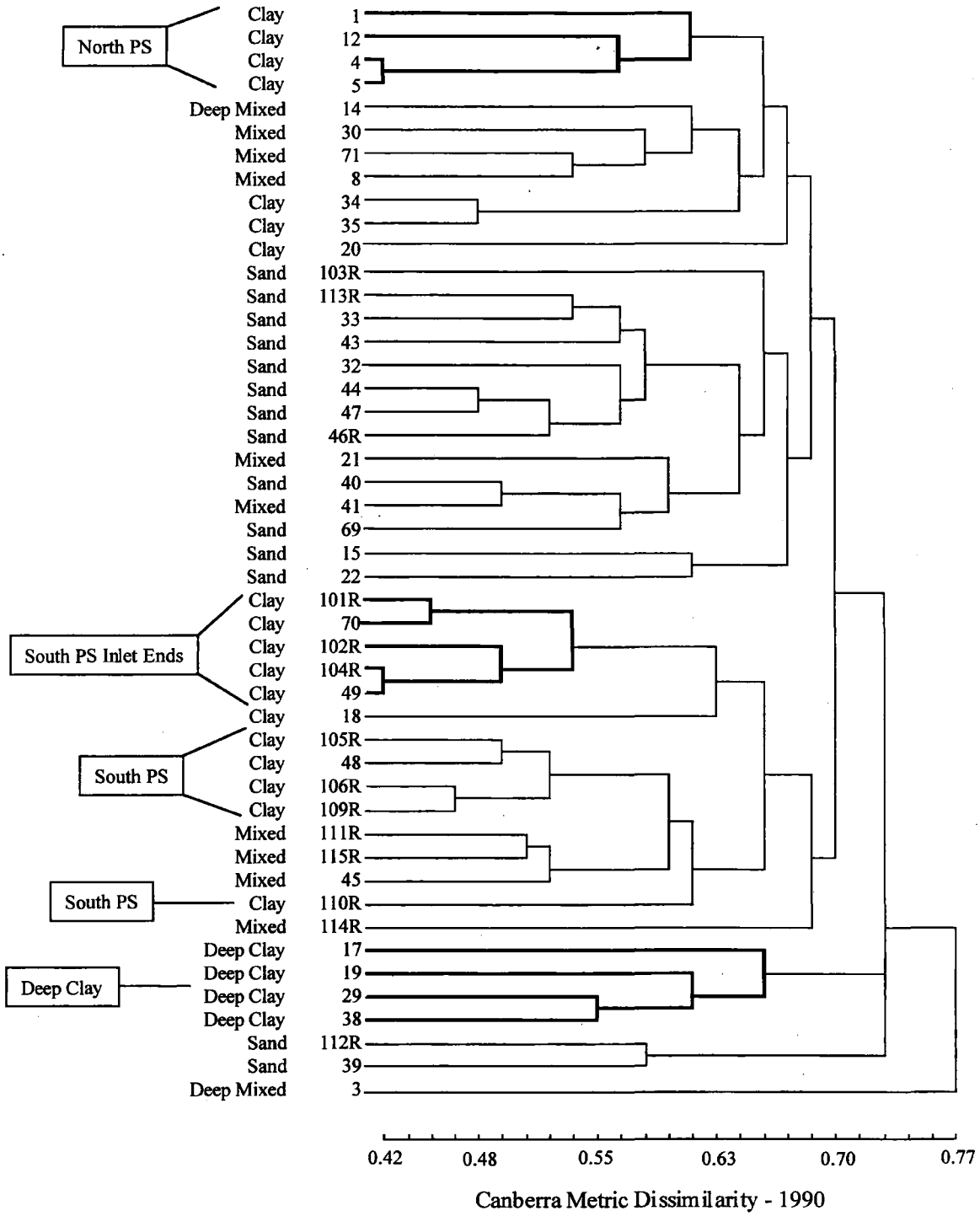

Figure 3. Dendogram showing classification of 47 stations in the Puget Sound region based on mean total abundannce of macrobenthos collected in 1990. Indicated in the dendogram is station number and sediment type.

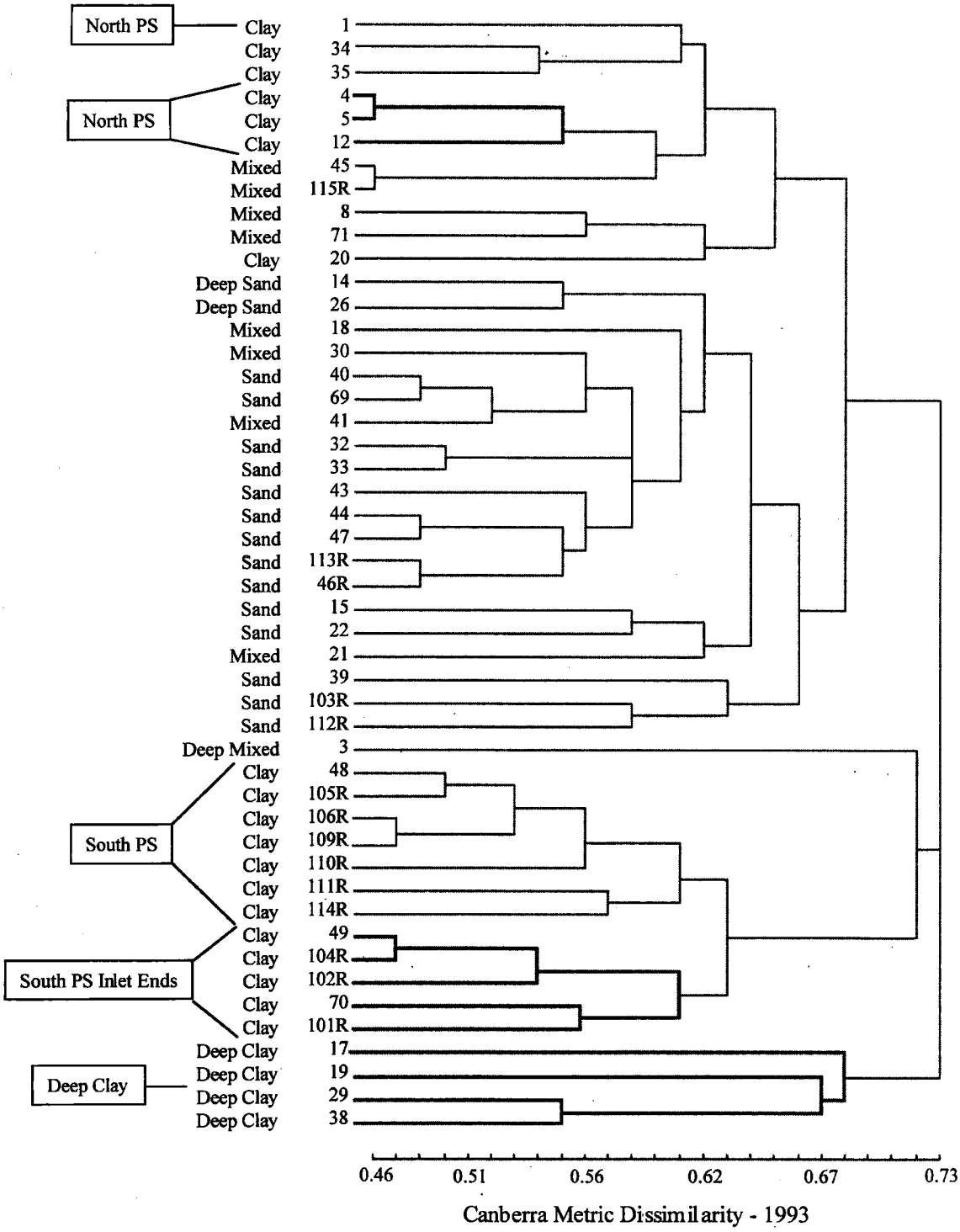

Figure 4. Dendogram showing classification of 48 stations in the Puget Sound region based on mean total abundance of macrobethnos collected in 1993. Indicated in the dendogram is station number and sediment type.

A few stations had low affinity with other stations. Among these, Station 3 in the Strait of Georgia was consistently separated from all others. Also, rotating Stations 305R in Hood Canal, 307R in Holmes Harbor, and 208R in Sequim Bay (not sampled in 1990 or 1993) had low affinity with other stations. These stations showed reduced faunal abundance and low species richness.

Dominant Species

The top numerically dominant species by sediment type are listed in Table 4. The majority of species in Puget Sound were not restricted to one substrate, but were broadly distributed in different types of sediment with peaks of abundance in sand, mixed sediment, or mud. Therefore, benthic infaunal communities in Puget Sound could only be loosely classified according to the type of substrate or water depth in which the species were dominant.

Table 4. Numerically dominant species in Puget Sound by sediment type. B=Bivalvia, C= Cumacea, D= Decapoda, E= Echinodermata, O= Ostracoda, P= Polychaeta.

Sand	Mixed
Euphilomedes carcharodonta (O)	*Axinopsida serricata* (B)
Prionospio jubata (P)	*Aphelochaeta* sp. (P)
Axinopsida serricata (B)	*Eudorella pacifica* (C)
Clay	**Deep Clay**
Amphiodia urtica-periercta (E)	*Macoma carlottensis* (B)
Eudorella pacifica (C)	*Axinopsida serricata* (B)
Sigambra tentaculata (P)	*Pectinaria californiensis* (P)

Some species (e.g., the echinoderms *Molpadia intermedia* and *Brisaster latifrons*) were restricted to deep water, and other species were characteristic of either north (e.g., the polychaetes *Cossura* sp. and *Levinsenia gracilis*) or south (e.g., the polychaete *Sigambra tentaculata*, and the bivalves *Macoma nasuta* and *M. yoldiformis*) Puget Sound clay sediments.

Discussion

The analysis of MSMP stations revealed rich and diverse assemblages of organisms (more than 1,000 species were collected) that were mainly associated with sediment type and water depth, reinforcing results from previous studies (e.g., Lie, 1974). In addition, some assemblages were separated secondarily by geographical location.

One group of stations consisted of inlet ends in south Puget Sound. Inlet ends were characterized by low species richness relative to other locations in Puget Sound. Although there was a tendency for stations with finer substrates to have lower number of species than stations with coarser substrates, clay stations in south Puget Sound supported fewer species than many shallow clay locations elsewhere. In addition, stations in south Hood Canal, Sequim Bay, Holmes Harbor, and the Strait of Georgia (Station 3) exhibited impoverished assemblages and were separated in cluster analysis.

One characteristic common to most of the above locations is their relative physical isolation from main basins that allow water exchange between the Puget Sound region and the continental shelf. Locations of restricted water circulation are prone to the development of seasonal episodes of low DO. If in addition these locations are associated with major inputs of fresh water, the likelihood is for the formation of seasonal density stratification of the water column, which exacerbates the low DO problem with increasing depth. Holmes Harbor and the Strait of Georgia are influenced by the extensive freshwater plumes of the Skagit and Fraser rivers, respectively.

The occurrence of low DO at south Hood Canal, Holmes Harbor, Sequim Bay, and Budd Inlet has been identified by Ecology's Marine Waters Monitoring Program (Newton et al., 1997). Additional data collected by the MSMP in south Hood Canal on two dates in September 1994 have demonstrated an

association between low DO (<2 $mg \cdot L^{-1}$) and reduced benthic abundance, with the greatest reduction in the crustacea (Llansó, unpublished).

Of course, low DO can only be hypothesized as one factor structuring benthic communities in Puget Sound. A gradual decline in species number is expected to occur along the estuarine gradient, as natural factors such as changes in water circulation, salinity, temperature, and sedimentation rates impose physiological and ecological barriers to the establishment of species populations.

Of special interest in monitoring programs are the relationships between indicator species and locations impacted by pollution. In the MSMP, the cirratulid *Aphelochaeta* sp. (mostly sp. C) was a dominant member of the community at urban stations where organic enrichment and/or moderate contamination were identified. For example, *Aphelochaeta* was numerically dominant near the City of Tacoma wastewater treatment plant WWTP outfall in Commencement Bay (Figure 5). However, elevated densities of this species were not found in any residential or rural areas, as illustrated for Quartermaster Harbor. Other monitoring programs in Puget Sound have found high densities of *Aphelochaeta* in contaminated areas, such as the Hylebos Waterway and the Harbor Island Superfund sites (Figure 5). The association of this species with organic pollution may be useful as an indicator of environmental conditions in Puget Sound.

Conclusions

Puget Sound exhibits rich infaunal assemblages that are primarily associated with sediment type and water depth, and secondarily with geographical location.

- Patterns in species abundance and composition appeared to be unrelated to low or moderate contaminant concentrations at sampling locations. Instead, there was an association between low abundance or species number and locations prone to the development of low-DO episodes.

  The identification of natural stresses in monitoring programs should be made a priority because these factors may confound interpretation of pollution effects.

- Twenty species showed large increases or decreases in abundance. The association of one of these species (*Aphelochaeta* sp.) with sediment contamination and organic enrichment may be useful as indication of pollution. Other pollution tolerant/sensitive species in the Puget Sound region should be identified.

- This study represents the first system-wide effort to characterize benthic assemblages in the Puget Sound region (Olympia north to the Canadian border and west to Port Angeles), and constitutes a first step toward the development of reference standards for assessing benthic environmental conditions in Puget Sound.

Acknowledgments

The MSMP is conducted by the Department of Ecology's Sediment Monitoring Team, which contributed substantially to this presentation. I am grateful to Brett Betts, Ken Dzinbal, and Rob Plotnikoff for reviewing a draft of this document.

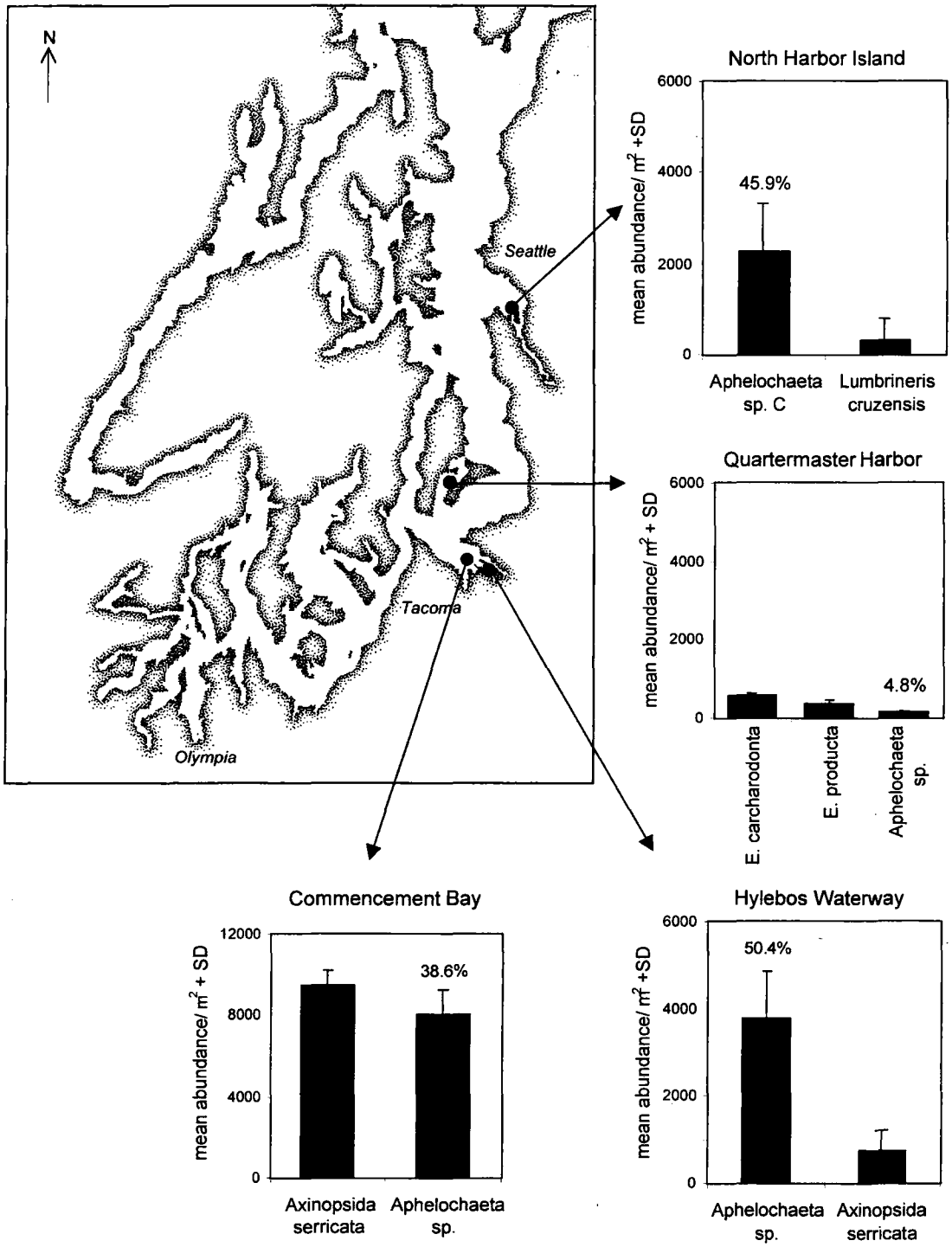

Figure 5. Top 2–3 numerically dominant species at four sites in Puget Sound. The percent contribution of the polychaete *Aphelochaeta* sp. to the total station abundance is indicated in the plots. Quartermaster Harbor Station 303R is a rural/residential area. Commencement Bay Station 41 is located near the outfall of Tacoma Central wastewater treatment plant. Hylebos Waterway Station 12 and North Harbor Island Station NH-08 are located in heavily contaminated areas. Selected stations have sediments with similar grain-size composition. Hylebos Waterway data collected by NOAA in 1994; North Harbor Island dada collected by EPA's Elliot Bay Action Program in 1985. *Axinopsida serricata* is a bivalve, *Euphilomedes carcharodonta* and *Euphilomedes producta* are ostracods, and *Lumbrineris cruzensis* is a polycheate.

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Pathways and Management of Marine Nonindigenous Species in the Shared Waters of British Columbia and Washington

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Abstract

The introduction of nonnative or nonindigenous species (NIS) to new environments can cause environmental and economic problems, although many NIS introductions are also considered beneficial. Pathways of NIS introduction to the shared marine waters of British Columbia and Washington include: aquaculture activities; the aquarium trade; public aquaria; releases of NIS by individuals; commercial, military, and recreational marine vessels; research institution;; and seafood commodity distribution. Risk of NIS introduction from aquaculture is well defined and the industry is highly regulated. Risk of NIS introduction from aquarium activities and release of NIS by individuals is poorly defined, and only limited information is available to define the risks from research, seafood distribution, and marine recreational vessel activities. The relative risk associated with the large inoculation of marine NIS from ballast-water discharges is assessed from shipping industry data.

More complete and detailed baseline information regarding the presence and distribution of native species and NIS in shared waters is needed, because in some cases, there is disagreement on whether particular species are native or introduced, or whether or not particular NIS are established. A zero-risk condition is unattainable; a more realistic objective of NIS management should be to reduce the frequency of unintended introductions, and to understand and minimize negative consequences of introduced species.

Biodiversity of Eelgrass and Infaunal Communities in the Intercauseway Area of Roberts Bank, B.C.

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R.W. Elner
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Abstract

Eelgrass beds alter the sedimentological and physico-chemical environments of tidal flats, impacting the distribution and abundance of infaunal populations. Expansion of a native eelgrass species, *Zostera marina*, and colonization of an exotic eelgrass species, *Zostera japonica* have been observed following construction and development of two causeways on Roberts Bank in the late 1960s. Eelgrass and infaunal communities and sedimentological properties were surveyed in October 1997 to determine the impact of expanding eelgrass beds on the biodiversity of infauna within the intercauseway area. Samples were collected along three station transects located at high-, mid-, and low-intertidal levels within this area and also at three reference stations on the north side of the Coal Port causeway for a comparison of pre- and post-causeway conditions. The high-intertidal transect is typified by microalgal biofilms, while the mid- and low-intertidal transects are dominated by *Zostera japonica*, and *Zostera marina*, respectively. An increase in biodiversity of infauna was observed with increasing eelgrass root biomass and decreasing tidal height. A comparison of infauna between the north and south side of the Coal Port causeway reveals a greater diversity of macrofauna within the intercauseway region. Shifts in infaunal communities associatied with the seasonal expansion and recession of eelgrass will be monitored over the next year to assess the trophic resource value of these eelgrass habitats for commercial fisheries and internationally migrating birds.

6C: Marine Biological Communities

Questions & Answers

Q: When you say contaminated, do you mean chemically contaminated sediments at a site?

Eaton: The test sites that we've been using to develop these biocriteria have had moderate to high levels of chemical contamination.

Q: What, besides presence or absence in an urban waterway justifies the assignment of sensitive vs. non-sensitive?

Eaton: Well, I guess "sensitive" has been defined by all of the sampling that has been conducted in contaminated environments over the last 18 years. So from all of the trawling that we've done in Superfund sites, fish species or categories of fish species that we encounter there with some regularity are obviously tolerant species or they wouldn't be present. And then species that, from reference areas of matched depth and sediment grain size and salinity, are present in much reduced numbers in the contaminated sites, we define them as being sensitive. But if a species is found in equal numbers or relatively equal numbers from the contaminated site compared to a reference site, we also would label that as a tolerant species.

Q: I guess, Charlie, continue on that. How do you know, in many of the same Superfund sites, there is a very large loss of preferred habitat. How do you know it isn't synergistic with that, or coincidental with loss of habitat vs. the contamination?

Eaton: Of course, it depends on which biological assemblage you're looking at. Each biological assemblage is looking at a different scale, or sampling a different scale. So the demersal fish populations, of course, are the largest scale, and the epibenthos is less mobile, a slightly smaller scale, and then the infauna would be the smallest scale of all. But you're right. For instance, in our initial phase in one comparison, we compared the Hylebos Waterway and the Blair Waterway, both of which don't have really natural, are not natural areas with, for instance, a natural tidal zone. There's a few in the Hylebos Waterway, a few little intertidal tiers, but not much. And that was probably one of the major problems with our choice of Quartermaster Harbor, comparing it to Thea Foss Waterway in phase two. I've lowered the priority of those metrics because of the fact that even though the physical parameters are well in line in September and late summer, if you did continuous monitoring of the physical parameters, Quartermaster Harbor would probably come out to be a different class than would be represented by one of the waterways. So it's probably better to compare a cleaner waterway to a dirtier waterway, rather than to a clean one, which is what we did in phase three.

Q: How many organisms were considered pollution tolerant? And the second question is, regarding the ecology of the communities you sampled, do you see communities that are more susceptible, more tolerant to change, as opposed to long-lived communities that, they usually call them type-three colonies, that take a long time to establish and are not used to disturbance?

Laetz: The first question, I looked into that, specifically one critter that's been widely used, *Capitella capitata*, a little polychaete worm. It was recovered in very low numbers and usually not at all in all of those samples. Conversely, there were some pollution-sensitive species, namely ophiuroids, brittle stars, that were collected at each station, which is a positive. The second question was about the type of communities that were found. A lot of the numerically dominant organisms were considered opportunistic species. But there were also some species present in relatively high numbers, although they weren't a dominant, such as *Lumbrineris*, it's a

polychaete worm that is considered relatively long lived, an indicator of a more stable community. But the numerically dominant ones were mostly opportunistic species.

Sutherland: [A poorly recorded response to an unrecorded question:] David Swindlakes did his thesis in that area, and he showed how they actually changed the topography of the tideflat. You can see the burrow openings in the mid-intertidal ... a smaller size fraction of macrofauna, but they burrow up to 50 centimeters and our core depths were only up to 10 centimeters. But that might be something to look at in the future: if they alter eelgrass or how eelgrass alters their environment.

Q: Did you do any correlation between elevation in the intertidal and other factors.

Sutherland: Yes, we looked at changes in sediment grain size and bulk density and water content along the tidal height. But what I tried to do was eliminate tidal factors in each of the transects by going across at the same tidal height. But we haven't yet done along shore or perpendicular to shore comparisons yet.

Q: Were mussels on the eelgrass or on the substrate?

Sutherland: Actually these mussels were collected from cores that were sieved. I'd say they were either within the sediment or on the surface. We haven't been examining the epifauna on the eelgrass. That's been done by other people, though.

Q: Did you get any fish in your beach seine samples? Did you see any juvenile rockfish or any other species?

Houghton: No juvenile rockfish. There were lots of juvenile flatfish, starry flounder, English sole, sand sole, lots of *Leptocottus*, of course. But the most dominant and most abundant, and we only did beach seining during the juvenile salmon out-migration, but we did catch tremendous numbers of very small surf smelt, so they really liked that in there.

Q: What was the total acreage of that marsh? And also, can you give kind of a ballpark of the costs associated with creating something like that?

Houghton: As far as the area within the lagoon of salt marsh plantings, I think we planted in the second year approximately a third of an acre. Then, as far as the cost goes, the monitoring costs have been, considering the baseline costs through the five-year post-construction monitoring, were $100,000-120,000, which the port paid. On the other hand, to take that material and dump it in deep water at the disposal site would have cost them at least that much because we used 300,000 yards of material that DNR would have charged us 50 cents a year to take to open-water disposal. So really, it was the classic win/win, I think.

Q: How did you keep the geese off the section that you planted?

Houghton: Well, we planted a little bit later. We did actually put up flashing red and silver tape and that may have helped. We also used more plugs the second time, because with the little shoots in that real soft mud the first year, they just grabbed a hold of it and yanked it out. But with the plugs, they could nibble at the top, but they couldn't actually destroy the plug. They would get some.

Q: We find geese predation for all the urban estuaries where you do restoration is one of the tough factors.

Houghton: Special hunting seasons would work.

PUGET SOUND RESEARCH '98

SESSION 7A

PROTECTION OF MARINE HABITATS

Session Chair:

James West
Washington State Department of Fish and Wildlife

Back to the Future: A Comparison of Ecosystem Structure of the Strait of Georgia 100 Years ago And Present Day

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Johanne Dalsgaard
Fisheries Centre, University of British Columbia

Introduction

Over the last 100 years humans have increasingly impacted marine ecosystems due to harvesting, pollution, and destruction of habitat. As a consequence, marine ecosystems observed today are different from a century ago. In this paper we construct past and present-day models of the Strait of Georgia ecosystem using Ecopath 3.0 modeling software (Christensen and Pauly, 1996a; Christensen and Pauly, 1996b). Recent fisheries literature and statistics were used as inputs for the present-day model, while a 100-year model was constructed using anecdotal, historical, and scientific sources from that period. To further validate the information, a workshop was held in November 1997, and suggested improvements were subsequently incorporated into the models. The main differences between the two models are explained by changes in relative abundance of organisms, which includes species now extirpated from the Strait. A comprehensive discussion of model inputs, methods, workshop discussions, and sources of information can be found in (Pauly et al., in press). In this paper, we summarize the methods used, the major differences between the two models, and a discussion of the implications.

Methods

The study area of the Strait of Georgia used in this project is defined by the body of water separating the British Columbia mainland and the Southern half of Vancouver Island between Campbell River (50° 05' N) and the southern Gulf Islands (48° 50'N). The area of this region is 6900 km^2, which is the value used as area input for the models.

An existing mass-balance model of the Strait of Georgia (Venier, 1996) served as a skeleton for building the present-day model. Ten functional groups were added and the model changed from a summer to a yearly average model. For many groups, the Ecopath input parameters including diet composition, production/biomass (P/B), consumption/biomass (Q/B), and/or ecotrophic efficiency (EE) remained unchanged, while the effort was concentrated on obtaining up-to-date biomass and harvest estimates from published scientific sources. Based on the present-day model, a model representing the Strait of Georgia 100 years ago (1890s) was constructed. Information for this model came from a variety of sources including traditional ecological knowledge, expert opinion, and historical sources (Wallace, in press). Two functional groups (sturgeon and baleen whales) were added, while other groups were modified when it could be documented that their abundance 100 years ago was different than today (Table 1). No changes of the P/B and Q/B values were made between the present-day and the 100-year model. For a full description of model inputs and flow diagrams see Dalsgaard et al. (in press).

Table 1. Biomass estimates of functional groups used in the two models of the Strait of Georgia. Dashes indicate that no value was entered.

Group / parameter	Present Biomass ($t \cdot km^{-2}$)	Past Biomass ($t \cdot km^{-2}$)	Ratio Past:present
Phytoplankton	31.1	31.0	Same
Kelp & sea grass	20.3	25.0	1.2
Herbivorous zooplankton	15.5	15.6	Same
Shellfish	220.5	220.5	Same
Grazing invertebrates	400.0	400.0	Same
Carnivorous zooplankton	33.3	32.3	Same
Predatory invertebrates	9.1	11.0	1.2
Shorebirds	0.001	0.002	2
Jellyfish	15.0	15.0	Same
Herring	6.0	7.0	1.2
Eulachon	0.7	1.3	2.0
Small pelagics	14.5	15.0	Same
Seabirds	0.02	0.02	Same
Misc. demersal fishes	12.6	38.0	3
Baleen whales	---	1.9	NA
Hake	35.5	9.0	0.25
Chinook & coho	0.7	6.5	10
Dogfish	8.7	8.7	Same
Sturgeon	---	0.02	NA
Transient salmon	6.4	13.0	2
Toothed whales	0.04	0.20	5
Halibut	0.004	0.14	35
Lampreys	0.2	0.2	Same
Lingcod	0.05	1.5	30
Seals & sea lions	0.6	0.47	0.8
Transient orcas	0.004	0.004	Same
Detritus	0	7.0	NA

Results and Discussion

The results observed fall into four categories of functional groups: 1) those that no longer exist in the Strait; 2) those whose relative abundance has changed; 3) those for which sources indicate no abundance change; and 4) those for which no historical sources are available and therefore are left the same as present.

Groups That No Longer Exist in the Strait

These results are the most interesting, because the ecological impact of completely removing a functional group has enormous ecological impact. There are three groups at present considered to be nonexistent from an ecological point of view: baleen whales (humpbacks), halibut, and sturgeon. Although some whaling took place in the Strait from 1866 to 1873, most of the whaling occurred in 1907–08. In that year alone, 97 humpbacks were harvested, many from the mouth of the Fraser River (Merilees, 1985). After just two years, all baleen whales had been killed. The presence of humpbacks, a large predator of herring in the Strait, would alter the flow of energy. Halibut is another top predator that was fished to ecological extinction early in the century. The biomass 100 years ago is only a crude estimate. Catch records from the Canada Sessional Papers (1897) listed a catch from 1896 of 0.142 $t \cdot km^{-2}$ landed at ports in the Strait. With no better data available, this figure was used as a biomass estimate for the Strait for the 100-year model. Sturgeon, although not found throughout the Strait, were in large abundance in the Fraser River Estuary—where, in 1897, 517 tons were landed (Echols, 1995). All three of these species, from an ecological point of view, disappeared close to a century ago and have yet to return.

Groups with Significant Changes in Abundance

There are numerous groups whose abundance has changed dramatically over the last 100 years. The most dramatic changes were found to be in lingcod, miscellaneous demersal fish, resident salmon, toothed whales, and hake. Lingcod supported a commercial fishery in the Strait from the 1870s to 1990. The estimate of lingcod 100 years ago was based on a model by Martell and Wallace (in press) that indicates that the biomass has decreased by 30 times. Lingcod are a top predator in structuring rocky reef fish communities. The loss of this substantial biomass has undoubtedly lead to cascading impacts throughout the system. Evidence from catch-per-unit-effort (CPUE) data on demersal fish (sole and rockfish) from Levy et al. (1996) showed that from the late 1970s to the early 1990s, the CPUE decreased to one-third of its original value. Based on this, the biomass of the group was conservatively assumed to have been three times higher 100 years ago. The resident stocks of chinook and coho salmon have decreased by an order of magnitude (Walters, pers. com.). The cause of salmon decline is likely a result of multiple factors. Toothed whales are composed of resident orcas and porpoises. Porpoises were an important component of Coast Salish diet, and bone remains have been found in many middens in the Strait of Georgia region (Calvert, 1980). Porpoise were also caught and combined with dogfish in the early reduction fisheries (Canada, 1887). No exact biomass data exist, but five times was used as an estimate. Finally, hake constitute the one functional group for which estimates of abundance are greater in the present model. It is thought that hake are occupying an ecological niche once used by lingcod and other demersal fishes.

Groups with No Abundance Changes

From Table 1, it is apparent that many groups have remained the same. This is either because information available suggests that the abundance has not changed, or there is no information available and therefore we assumed the same value. Considering how difficult it is to get present-day estimates of certain groups, it is not surprising that data for 100 years ago do not exist. This is true for many of the lower trophic-level invertebrates. More interesting are groups such as dogfish and herring, for which information sources exist, but yet the abundance is considered to be the same as today. Both of these species are considered to be important components in structuring the ecosystem of the Strait.

Herring was the most controversial input of the mode,l because it is both an ecologically important group and also the center of a continuous political debate. The final biomass used was based on expert opinion that suggested that the overall present-day biomass was equal to historic levels (Wallace, in press). The difference is that the Strait once supported numerous year-round resident stocks that may have composed one-third of the biomass. At present, the migratory stock makes up 95% of the herring biomass and uses a smaller area of the Strait when present. The overall amount of herring available to other species has likely decreased (Dalsgaard et al., in press).

Conclusion

Although many gaps in knowledge exist regarding the structuring of ecosystems, it is agreed upon that the Strait of Georgia has undergone an ecological transformation from the effects of human predation on marine organisms. Presumably, if overharvesting (or any other human activity) is responsible for the declines, then it is possible from an ecological point of view to rebuild the system. Rebuilding of ecosystems from a single species perspective cannot work due to the complexities and uncertainties of marine species and systems. Based on theories of ecosystem development, total biomass accumulates as an ecosystem moves towards maturity (Odum, 1969; Christensen and Pauly, 1998). To rebuild a system requires a decrease in biomass removal of all species. Marine protected areas where human harvest is limited have shown to be effective in building up biomass and restoring ecological processes, and may be the best way to approach the problem.

Acknowledgments

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The Status of Marine Protected Areas in Puget Sound

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Introduction

In recent years, a strong interest in marine protected areas (MPAs) has emerged and taken hold in Washington State and British Columbia. In 1994, the British Columbia/Washington Marine Science Panel recommended, with high priority, that MPAs be established in Puget Sound and Georgia Basin to protect marine habitat and resource populations (Marine Science Panel, 1994). The Washington Marine Protected Areas Work Group formed in 1995 with a goal of developing a common strategy for identifying and establishing a network of MPA sites (Washington MPA Work Group, 1998).

Sound planning for the development a system of MPAs requires a basic understanding of existing protected sites and supporting institutional arrangements. However, the collection of MPAs in Puget Sound is poorly understood, scarcely documented, and not yet represented in any comprehensive map or geographic information system (GIS). Furthermore, existing MPAs have evolved from a fragmented and confusing mix of management policies, independent programs, and legislative and administrative actions.

A marine protected area, as defined by the International Union for the Conservation of Nature and Natural Resources (IUCN), refers to "any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment" (IUCN, 1988). MPAs are areas specially managed to protect species, habitats and ecosystems; they are marine areas set aside from otherwise unrestricted human activities. World-wide, MPAs have been described by a wide variety of protected area titles, including marine reserves, preserves, parks, sanctuaries, refuges, wilderness areas, protected areas and many other terms.

MPAs may range along scales of size and protection level from small "no-intrusion" areas, to "no-take" reserves prohibiting all consumptive human uses, to large multiple-use areas balancing a whole range of conservation, economic and social objectives, and innumerable possibilities in between (Kelleher and Kenchington, 1992; Sobel, 1993; Eichbaum et al., 1996; Gubbay, 1995; Agardy, 1997). Though often controversial, MPAs are credited with a long list of potential benefits. MPAs can help to: protect biodiversity and ecosystem structure, function and integrity; improve fishery yields and management; expand knowledge and understanding of marine ecosystems; provide recreation and tourism opportunities; and provide socio-economic benefits for coastal communities (Salm and Clark, 1984; Ballentine, 1991; Bohnsack, 1993; Sobel, 1993, 1996; Gubbay, 1995; Agardy, 1997).

Objectives

The purpose of the study, as commissioned by the Puget Sound Water Quality Action Team (PSWQAT) with funds from the U.S. Environmental Protection Agency, was to compile a centralized information source on Puget Sound marine protected areas for the Washington MPA Work Group. Compiled as a comprehensive document, a report is currently (as of March 1998) under final review by the PSWQAT. Primary objectives of the study were to:

- Identify and profile existing MPAs in Puget Sound;
- Identify and review existing institutions and designation mechanisms responsible for the establishment and management of the current system of MPAs; and

- Summarize and evaluate the overall system of MPA sites and institutional arrangements.

Methods

Intertidal and subtidal protected areas in Puget Sound were identified from a review of available literature, which proved to be limited and scattered. Numerous interviews were also conducted with protected area site managers or staff, government agency staff involved with protected area programs, state and local government planners, researchers, volunteers, and many others. Protected areas investigated were primarily those of state or federal designation, established through December, 1997. To keep the study at a manageable size, local government and private sector designations were not fully investigated in this preliminary assessment. Primary institutional focus was placed on state and federal agency roles in MPA establishment and management; less detailed reviews were conducted on the MPA involvement and efforts of Treaty Tribes, local governments, and various private sector organizations.

In profiling MPAs, the type of information sought for each site can be roughly characterized as fitting into three categories: 1) general site information; 2) geographic information; and 3) site protection and management. General information collected included site name; designation type; date of establishment, establishing and managing agency or organization, purpose and objectives, and legal authority. Geographic information collected included location; marine boundary identification and description; identification of overlapping or abutting MPAs; and size/acreage breakdown (if possible) for upland, intertidal and subtidal components. Finally, in order to understand the level of protection specifically provided to marine species and habitats, and to gain perspective on the extent and nature of on-site management activities, the following information was sought for each site: legal citation and description of site-specific restrictions on human activities to protect marine resources; description of other marine resource protection mechanisms (proprietary access controls, voluntary compliance approaches, etc.); management or master plan status, and marine resource emphasis therein; extent and nature of site supervision and enforcement; and general information on site-specific programs for research, monitoring, education, or public involvement. Detailed ecological assessments or information related to site effectiveness were not pursued.

Results

Results presented here are a sub-set of highlights from the findings and analysis contained in the 1996–97 study. Primary emphasis is placed on MPA site characteristics, with less discussion of institutional arrangements.

MPAs Identified

A total of 102 Puget Sound intertidal and subtidal protected areas were identified as existing MPAs (Table 1). Also identified were five proposed sites under consideration for designation as of December 1997. Additionally, a variety of "possible" MPAs were identified. For these sites MPA determination was questionable due to lack of available data or uncertainty as to whether or how the site provides marine area protection.

Detailed site profiles were created for 42 of the 102 identified sites; state parks were not individually profiled because a centralized collection of similar information is already documented and maintained by the Washington State Parks and Recreation Commission (WSP&RC, 1996).

Table 1. Puget Sound Marine Protected Areas.

Name or Location	Designation	Agency/Organization
1. Friday Harbor to Point Caution	San Juan Islands Marine Preserve Area	WDFW; FHL
2. Yellow and Low Islands	San Juan Islands Marine Preserve Area	WDFW; FHL
3. False Bay	San Juan Islands Marine Preserve Area	WDFW; FHL
4. Argyle Lagoon	San Juan Islands Marine Preserve Area	WDFW; FHL
5. SW Shaw Island	San Juan Islands Marine Preserve Area	WDFW; FHL
6. San Juan County/Cypress Is.	Marine Biological Preserve	FHL
7. Padilla Bay	National Estuarine Research Reserve	Ecology
8. Edmonds Underwater Park	Underwater Park	City of Edmonds
9. Sund Rock	Marine Preserve Area	WDFW
10. Haro Strait	Special Management Fishery Area	WDFW
11. San Juan & Upright Channel	Special Management Fishery Area	WDFW
12. Point Lawrence	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
13. Bell Island	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
14. Charles Island	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
15. Pile Point	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
16. Lime Kiln Lighthouse	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
17. Kellett Bluff	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
18. Gull Rock	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
19. Bare Island	Voluntary No-Take Bottom Fish Recovery Area	San Juan County
20. Dabob Bay	Natural Area Preserve	DNR
21. Kennedy Creek	Natural Area Preserve	DNR
22. Skookum Inlet	Natural Area Preserve	DNR
23. San Juan Islands (83 rocks, reefs and islands)	National Wildlife Refuge	USFWS
24. Protection Island	National Wildlife Refuge	USFWS
25. Zella M. Schultz/Protection Is.	Seabird Sanctuary	WDFW & USFWS
26. Tongue Point	Marine Life Sanctuary	Clallam County
27. Yellow Island	Nature Conservancy Preserve	TNC
28. Chuckanut Island	Nature Conservancy Preserve	TNC
29. Foulweather Bluff	Nature Conservancy Preserve	TNC
30. Goose Island	Nature Conservancy Preserve	TNC
31. Deadman Island	Nature Conservancy Preserve	TNC
32. Sentinel Island	Nature Conservancy Preserve	TNC
33. Waldron Island	Nature Conservancy Preserve	TNC
34. Lummi Island	Natural Area Preserve	WDFW
35. Kimball Preserve, Decatur Is.	San Juan Preservation Trust Preserve	SJPT
36. South Puget Sound	Wildlife Area	WDFW
37. Titlow Beach	Marine Park / Marine Preserve	METRO/Tacoma
38. Cypress Island	Natural Resources Conservation Area	DNR
39. Woodard Bay	Natural Resources Conservation Area	DNR
40. Dungeness	National Wildlife Refuge	USFWS
41. Nisqually	National Wildlife Refuge	USFWS
42. Skagit	Wildlife Area	WDFW
43. Sequim Bay State Park	State Park	WSP&RC
44. Camano Island State Park	State Park	WSP&RC
45. Deception Pass State Park	State Park	WSP&RC

Table 1 (cont.). Puget Sound Marine Protected Areas.

Name or Location	Designation	Agency/Organization
46. Ebey's Landing	State Park	WSP&RC
47. Fort Casey State Park	State Park	WSP&RC
48. Fort Ebey State Park	State Park	WSP&RC
49. Joseph Whidbey State Park	State Park	WSP&RC
50. South Whidbey State Park	State Park	WSP&RC
51. Dosewallips State Park	State Park	WSP&RC
52. Fort Flagler State Park	State Park	WSP&RC
53. Fort Worden State Park	State Park	WSP&RC
54. Mystery Bay Marine State Park	State Park	WSP&RC
55. Old Fort Townsend State Park	State Park	WSP&RC
56. Pleasant Harbor State Park	State Park	WSP&RC
57. Triton Cove State Park	State Park	WSP&RC
58. Dash Point State Park	State Park	WSP&RC
59. Saltwater State Park	State Park	WSP&RC
60. Blake Island State Park	State Park	WSP&RC
61. Fay Bainbridge State Park	State Park	WSP&RC
62. Fort Ward State Park	State Park	WSP&RC
63. Harper State Park	State Park	WSP&RC
64. Illahee State Park	State Park	WSP&RC
65. Kitsap Memorial State Park	State Park	WSP&RC
66. Manchester State Park	State Park	WSP&RC
67. Old Man House State Park	State Park	WSP&RC
68. Scenic Beach State Park	State Park	WSP&RC
69. Belfair State Park	State Park	WSP&RC
70. Harstine Island State Park	State Park	WSP&RC
71. Hope Is. (S.) Marine State Park	State Park	WSP&RC
72. Jarrell Cove State Park	State Park	WSP&RC
73. McMicken Is. Marine State Park	State Park	WSP&RC
74. Potlatch State Park	State Park	WSP&RC
75. Squaxin Island State Park	State Park	WSP&RC
76. Stretch Point State Park	State Park	WSP&RC
77. Twanoh State Park	State Park	WSP&RC
78. Cutts Island Marine State Park	State Park	WSP&RC
79. Eagle Island Marine State Park	State Park	WSP&RC
80. Joemma Beach State Park	State Park	WSP&RC
81. Kopachuck State Park	State Park	WSP&RC
82. Penrose Point State Park	State Park	WSP&RC
83. Blind Island Marine State Park	State Park	WSP&RC
84. Clark Island Marine State Park	State Park	WSP&RC
85. Doe Island Marine State Park	State Park	WSP&RC
86. James Island Marine State Park	State Park	WSP&RC
87. Jones Island Marine State Park	State Park	WSP&RC
88. Lime Kiln State Park	State Park	WSP&RC
89. Matia Island Marine State Park	State Park	WSP&RC
90. Moran State Park	State Park	WSP&RC
91. Patos Island Marine State Park	State Park	WSP&RC
92. Posey Island Marine State Park	State Park	WSP&RC
93. Spencer Spit State Park	State Park	WSP&RC
94. Stuart Island Marine State Park	State Park	WSP&RC
95. Sucia Island Marine State Park	State Park	WSP&RC

Table 1 (cont.). Puget Sound Marine Protected Areas.

Name or Location	Designation	Agency/Organization
96. Turn Island Marine State Park	State Park	WSP&RC
97. Bay View State Park	State Park	WSP&RC
98. Larrabee State Park	State Park	WSP&RC
99. Saddlebag Is. Marine State Park	State Park	WSP&RC
100. Mukilteo State Park	State Park	WSP&RC
101. Tolmie State Park	State Park	WSP&RC
102. Birch Bay State Park	State Park	WSP&RC

DNR = Washington Dept. of Natural Resources
Ecology = Washington Dept. of Ecology
FHL = University of WA Friday Harbor Laboratories
METRO/Tacoma = Metropolitan Park District of Tacoma
SJPT = San Juan Preservation Trust
TNC = The Nature Conservancy
USFWS = Untied States Fish & Wildlife Service
WDFW = Washington Department of Fish & Wildlife
WSP&RC = Washington State Parks and Recreation Commission

MPA designation types are highly varied, with 14 different institutional designations represented. These protected area designations are associated with a variety of federal, state and local government programs, as well as some private sector mechanisms (Table 2).

Table 2. Institutions and designation mechanisms associated with existing MPAs in Puget Sound.

Institution	Designation Types (for existing MPAs only)
WASHINGTON STATE	
Department of Natural Resources (DNR)	Natural Area Preserve
	Natural Resources Conservation Area
Department of Fish and Wildlife (WDFW)	Marine Preserve Area
	Special management fishery area
	Wildlife Area
	Seabird Sanctuary
Parks and Recreation Commission (WSP&RC)	State Parks (developed)
Department of Ecology	National Estuarine Research Reserve
University of Washington Friday Harbor Laboratories	Marine Biological Preserve
FEDERAL	
U.S. Fish and Wildlife Service (USFWS)	National Wildlife Refuge
National Oceanic and Atmospheric Administration (NOAA)	National Estuarine Research Reserve
LOCAL GOVERNMENT	
City of Edmonds	Underwater Park
City of Tacoma	Marine Preserve
Clallam County	Marine Life Sanctuary
San Juan County	Voluntary Bottomfish Recovery Area
PRIVATE SECTOR	
The Nature Conservancy	Preserve
San Juan Preservation Trust	Preserve

Missing Site Information

At the site level, much information was found to be missing or unobtainable within the scope of this study. There is a general lack of documented details concerning the marine components (intertidal and subtidal portions) of many protected areas. Site elements of interest for this study that were most commonly unavailable or unclear included the following:

- Clear identification and description of marine boundaries.
- Size/acreage breakdown for intertidal and subtidal components. Surveys to measure, or existing information on, the size of marine areas contained within protected areas is often not performed or available. With scattered data, information on size and area is often inconsistent.
- Information on marine resources (natural and/or cultural) and resource values, specific to the site. The resource information base from which many protected areas operate, especially but not exclusively those that are primarily land-attached, lacks emphasis on the marine environment contained within and adjacent to site boundaries.

Geographic Distribution and Characteristics

Geographic distribution of MPAs is varied, with roughly equal distribution between northern and southern Puget Sound. A high concentration of sites is located in the San Juan Archipelago, while there is a relative lack of sites along the Strait of Juan de Fuca. MPAs that are part of terrestrial protected areas dominate in number (82% of total), while subtidal sites are minimal (18%). The sizes of Puget Sound MPAs vary dramatically. Subtidal sites with legal closures on harvest are small (10 to 200 acres) relative to large intertidal protected areas (ranging from 2000 to 13,000 acres).

Marine Area Protection Approaches

Most MPAs in Puget Sound contribute to the protection of marine species, habitats or ecosystems through one of two distinct approaches: regulatory mechanisms (based in specific laws, such as prohibitions on harvest) or proprietary mechanisms (based on property ownership or lease). To a limited extent, regulatory approaches have been used in the subtidal environment to provide long-term area-specific harvest closures to manage fisheries, provide non-consumptive recreational opportunities, or facilitate scientific research. More common among Puget Sound MPAs is the application of a proprietary approach to marine area protection. This can involve the acquisition and set-aside of intertidal areas, placing of limits on land-based human access or activities, and/or the withdrawal (by DNR) of certain public aquatic lands from availability for lease. In recent years, some MPAs have been planned and established through an integration of these two historically separate approaches (e.g., Titlow Beach Marine Preserve). Additionally, the recent establishment of eight Voluntary No-take Bottom Fish Recovery Areas in San Juan County has introduced a possible third approach to marine area protection: voluntary compliance MPAs.

Protection Of Fished And Unclassified Marine Species

Only 18 (18%) of the 102 MPAs identified in the study provide protection from harvest for fished species (those classified as food fish, game fish and shellfish by the Washington Department of Fish and Wildlife) (Figure 1). Eight of these 18 harvest refugia sites are voluntary compliance MPAs; thus, only 10% of identified MPAs actually provide legally based harvest closures for fished species. The vast majority of MPAs (82%) do not directly restrict fishing activities, although some sites limiting public access do so indirectly.

The harvest or collection of unclassified species is legally prohibited at 62 MPAs (60% of sites), with State Parks representing 97% of that total (Figure 2). As of 1997, there is only one no-take MPA in Puget Sound (Edmonds Underwater Park) prohibiting the extraction of all marine life.

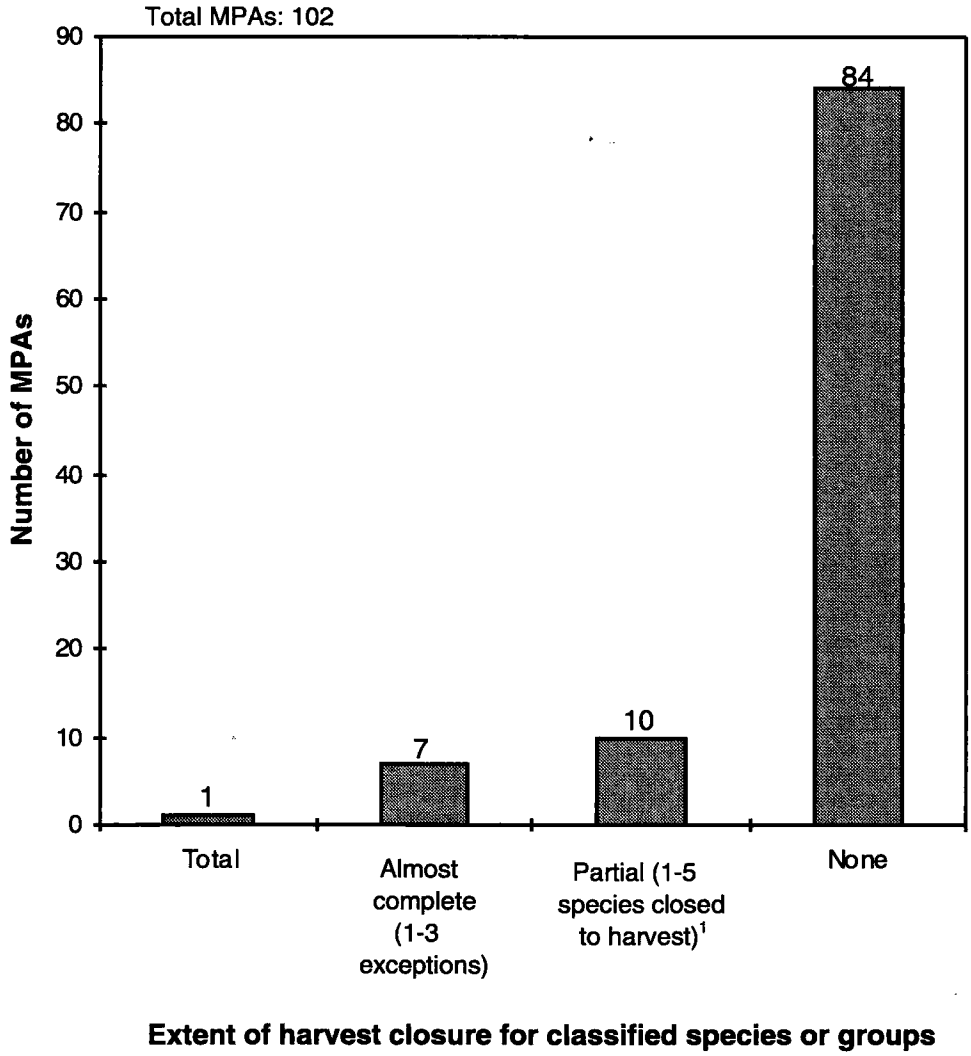

Figure 1. Extent of protection from harvest for classified species provided by MPAs in Puget Sound. Includes eight voluntary MPA's. Classified species are those designated as game fish, food fish, or shellfish by the Washington Department of Fish and Wildlife, which represents San Juan County Cypress Island Marine Biological Preserve, administered by the University of Washington's Friday Harbor Laboratories.

MPA Site Management

The nature and extent of on-site management activity occurring at MPAs in Puget Sound is highly varied. Significant management differences exist among sites that range from set-aside areas with minimal supervision and management activity, to research reserves featuring continuous on-site management developments and activity.

Many MPAs are observed as being actively managed on site, with, at a minimum, management staff present and regular maintenance and supervision provided. Examples of such sites include the Padilla Bay National Estuarine Research Reserve (NERR), the Nisqually and Dungeness National Wildlife Refuges, Edmonds Underwater Park, State Parks, and other sites. A number of other protected areas, however, receive significantly less management attention. Examples of MPAs where site management attention is considered low include Natural Area Preserves at Dabob Bay, Kennedy Creek, Skookum Inlet, and Lummi Island; the San Juan Islands National Wildlife Refuge; and the Sund Rock Marine Preserve. While at some sites active management is not an objective or need, in

most cases resource limitations have prevented implementation of originally intended or envisioned levels of management.

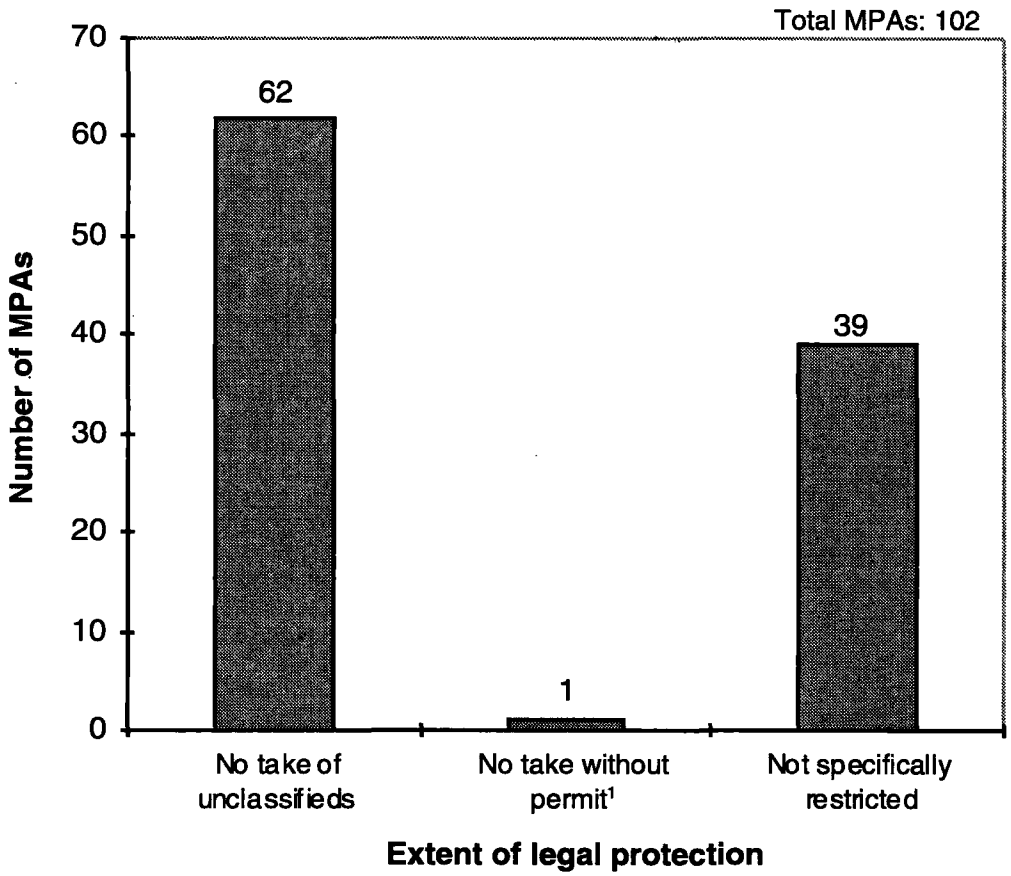

Figure 2. Number of MPAs that prohibit the harvest or collection of unclassified marine species by law. Unclassified marine species are those that have not been designated by the Washington Department of Fish and Wildlife (WDFW) as food fish or shellfish. As used here, protected by "law" refers to harvest or collection restrictions specified in state laws or local ordinances, and as such is not inclusive of management attempts to prohibit intertidal harvesting through proprietary access restrictions or other management measures.

More than 75% of the MPAs identified in this study are managed without the guidance of a completed site-specific management plan. For most of these sites, site management is guided by centralized planning or direction contained within geographically broader plans. However, approximately nine MPAs appear to have no management plan at all, specific or general. At many sites, new or updated management plans are currently being developed (e.g., four National Wildlife Refuges, two Wildlife Areas, Padilla Bay NERR, some State Parks, and others).

Year-round on-site management presence is found at approximately 71 sites. Remaining sites are visited by management staff on an infrequent basis, such as seasonally, a few times per year, or as incidents require. For those MPAs with harvest prohibitions in place, very few have developed site-specific enforcement programs. When interviewed, management staff and others familiar with particular MPAs most often characterized official enforcement presence and site supervision as light.

Educational approaches to achieve compliance are more commonly employed. Beach watch programs in place at MPAs such as Edmonds Underwater Park and Titlow Beach Marine Preserve provide site supervision and enforcement notification. The regular presence of volunteer divers and educational efforts of citizen park stewards at Edmonds have created strong peer pressure and an environmental ethic. As a result, the site is generally "self-policing."

Indirect or unofficial supervision is also common at many MPAs, whereby various parties keep watch, reporting violations and often approaching and educating potential violators. These parties include local residents, volunteers, researchers, maintenance staff, and others, but they are usually not responsible for site supervision or enforcement.

Conclusions

The diverse set of protected intertidal and subtidal areas found in Puget Sound have developed incrementally and inconsistently into a patchwork of MPAs which vary considerably in designation, purpose, resource protection offered and level of management provided. Many organizations are involved in governing and managing resources and activities in Puget Sound. The study found that five state government institutions and two federal agencies are primarily responsible for the majority of the existing 102 MPAs identified. Local governments and various private sector organizations can also establish several types of MPAs.

The existing institutional structure to support MPA establishment and management in Puget Sound is fragmented and complex. There has been no clear policy or coordinated program to guide the region's establishment and management of MPAs. Designations have occurred without systematic consideration of overall objectives, site identification criteria, design, financing, designation, management, monitoring and evaluation.

However, a diverse set of marine area protection mechanisms and tools do exist. Among the various entities involved, adequate authority exists to create MPAs ranging from small strictly regulated no-take or no-intrusion areas, to larger multiple use protected areas providing for the management of many uses. MPAs are a tool available to many agencies and organizations that may be useful for a variety of management functions.

In Puget Sound, most existing MPAs have been established and are operated through the independent efforts of a single agency or organization pursuing the fulfillment of a particular mandate or goal. Multi-institutional planning for and operation of sites is not the standard, but is found at some MPAs.

The most common type of MPA observed in Puget Sound is one that is attached to a terrestrial park or other protected area containing a fringing intertidal border. The extent and nature of resource protection focused on the intertidal portion of such areas is highly variable. In terms of the number and size of site designations and depth of management experience, it is clear that MPA developments in Puget Sound (especially for subtidal areas) lag well behind terrestrial protected area developments. Only 18 subtidal- and intertidal-only MPAs are identified, and of these, 15 have been established within the last 10 years. These areas are truly special features, rather than the standard.

At subtidal sites where fishing is restricted, it is uncommon for all forms of harvest to be prohibited. With only one complete no-take site (Edmonds Underwater Park), the region has as of yet little experience in establishing and managing areas reserved from all extractive use.

Recommendations and Applications

Moving Toward a Complete MPA Inventory

Building on the data collected, it is recommended that steps be taken to move this preliminary assessment toward a more complete MPA inventory for Puget Sound. A geographic information system (GIS) and database for MPAs should be developed and maintained. Additionally, research should be undertaken to identify various additional MPA sites and designation mechanisms of local government and private sector origin. Consideration might also be given to expanding MPA identification and profiling efforts state-wide, and integrating results with British Columbia. For existing MPAs where site data is scarce, it would be wise to gather additional information on such

basic elements as marine area boundaries and site-specific marine resource features and values.

Ultimately, if a coordinated system or network of MPAs is to be developed throughout Puget Sound and the Georgia Basin, all programs, potential partners and protected sites should be represented within a comprehensive MPA inventory. Ideally, it is recommended that development of a distributed, possibly on-line, system for gathering, maintaining and sharing new and updated basic information on protected areas be investigated. In short, it would seem wise to take necessary steps to maintain and build on the study's data, thus preventing or reducing the future possibility of a large scale effort to reassess the basic status of MPAs in Puget Sound.

Applications

While the study's compilation of information does not simplify the complexity of the existing system, it can help eliminate some confusion about Puget Sound MPAs. It is hoped that this information can help interested individuals to better understand the system as it currently exists.

As efforts advance toward the design of a system or network of MPAs, the information collected in this study can serve as a preliminary baseline measure of the extent of marine area currently protected. As much focus is given to the establishment of new sites, this information can also help draw attention to existing protected areas in Puget Sound. To this end, opportunities may be explored to improve, enhance, build upon and learn from existing MPAs. This may help increase dialog between groups, and bring to light potential cooperative and partnership opportunities within and between agencies and organizations.

The centralized source of information on Puget Sound MPAs may also serve as a base from which higher level studies and system analysis work can begin. In addition to research and work directed at expansion and improvement of an MPA inventory for the region, this information base might invite additional studies on such topics as MPA effectiveness or funding sources and needs.

Overall, it is hoped that the compilation of information on existing MPAs can provide a foundation upon which to build a more rational, effective, coordinated and manageable system of MPAs in Puget Sound.

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Development of a Marine Protected Areas Strategy for Washington State

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History

Both world-wide literature and local data point to the value of marine protected areas for a variety of marine resources and habitats (Palsson and Pacunski, 1995; British Columbia/Washington (BC/WA) Marine Science Panel (MSP), 1994; Rowley, 1994; Shackell and Willison 1995; West 1997). These areas can also be used to provide more holistic management of the resources in a given area (Agardy, 1998). The local research has provided more than just academic arguments in favor of establishing these areas. Within Puget Sound, the work by Palsson and Pacunski has been pivotal in development of policy on marine protected areas. It has also been a fundamental feature in outreach and education about such areas. The demonstration of the changes in the fish populations and fecundity is persuasive information that tends to win over the most ardent skeptics in public meetings.

Development of a strategy to design and implement a network of marine protected areas has been a multiagency effort in Puget Sound. This is in sharp contrast to the way many of the existing protected areas were developed. Many different agencies have the authority to protect sites, either through regulatory or proprietary means. In addition, the existing areas were developed piecemeal by individual agencies acting, with little consultation with others (Marine Protected Area Work Group, 1998).

Puget Sound-Georgia Basin (PSGB) Task Force

In 1994, the PSGB Task Force was established by the Environmental Cooperation Council in 1994 to respond to the recommendations of the Marine Sciences Panel report (British Columbia/Washington (BC/WA) Marine Science Panel (MSP), 1994). One of the recommendations was to establish marine protected areas to help reverse the declining trend in a variety of fish and wildlife resources in the area. The Task Force prioritized the recommendations of the Marine Sciences Panel and established work groups with branches in Washington and British Columbia to deal with the top four items. The Washington Marine Protected Area Work Group was started in 1995. Since British Columbia had already been working on establishment of marine protected areas, the interagency group in place there served as the B.C. branch of the Work Group.

In Washington, the Work Group's initial planning called for design of a system of marine protected areas and included a series of outreach meetings. Understanding of the concepts and support by current users of the sites was considered crucial to the success of the network. This consideration was based on observations of the existing sites, such as Edmonds, which were working well (Palsson, 1997). This consideration also seemed to parallel the course taken by the British Columbia group.

This approach was criticized by some of the Marine Science Panel members and by others who recommended that protected areas be established as expeditiously as possible. The Task Force asked the Work Group to add efforts to develop and establish some marine protected areas quickly. The Washington Work Group then drafted a list of potential sites based on interviews with a few recognized experts. As evaluation began, the Work Group recognized that it did not have the expertise to evaluate the sites technically. In addition, the political reality was that such a list could generate great opposition if existing users in the area did not feel they were involved with development or that the agencies were moving forward with less than adequate evaluation.

This was reported to the Task Force in early 1997 and the Task Force clarified the role of all the Work Groups. Since only the agencies with management authority can implement the recommendations, the Work Group products should be more detailed reports on the actions needed to effect the changes. The actual implementation, appropriately, would come via normal agency functions. In short, the Work Groups needed to plan rather than implement.

Draft Strategy

With that information in hand, the Marine Protected Area Work Group produced a draft strategy in January of 1998. The strategy calls for an interagency effort to design and implement a network of marine protected areas. The management structure recommended to accomplish this is modeled after the Puget Sound Ambient Monitoring Program. The key elements are: 1) a draft policy for marine protected areas in Washington; 2) evaluation of sites by a policy and a technical committee; 3) strong involvement by the public, tribal cooperative managers and local governments; 4) use of the precautionary approach; 5) evaluation of the outcomes at individual sites; and 6) adaptive management. The draft strategy was circulated for public comment and is currently under revision. Comments to date have recommended that the process be re-drafted with less emphasis on the evaluation and more discussion of the public involvement sections. This re-drafting is now underway.

What Happens Next

When revisions are complete and acceptable to the Work Group, the strategy and recommendations will be forwarded to the Puget Sound-Georgia Basin International Task Force. The Task Force will have the option of forwarding the documents on to the Environmental Cooperation Council (ECC) or to other Work Groups established by the Task Force. The ECC, in turn, may make recommendations to the state and the province including the agencies with jurisdiction which must effect changes needed to bring reversal in the declining trends in these resources. Any actions recommended here and pursued by these management agencies will be subject to full agency review including the public participation and comment process of the organization involved.

Other Marine Protected Area Activities Underway

While this strategy was in development, several other events were taking place. Two Washington State agencies have policies in development regarding marine protected areas (the Department of Natural Resources and the Department of Fish and Wildlife). The development of the interagency strategy, in part, prompted examination of the issue within the agencies. The draft Fish and Wildlife policy was to be presented to the Fish and Wildlife Commission in a workshop on March 21, 1998. The Commission was scheduled to consider adoption of the draft policy in June 1998 (Washington Department of Fish and Wildlife, 1998c).

The concept of marine protected areas for specific species was included in two policies adopted by the Fish and Wildlife Commission in the last year. The Forage Fish Policy and the Wild Salmonid Policy both contain provisions for creation of marine protected areas for species including forage fish in marine waters (Washington Department of Fish and Wildlife, 1998b and 1997b). Marine protected areas are an integral part of the Puget Sound Groundfish Management Plan under development by the Department of Fish and Wildlife. This also was to be brought to the Commission for a workshop in March and for adoption in June, 1998 (Washington Department of Fish and Wildlife, 1998e).

In addition, Fish and Wildlife staff discussions with environmental groups and recreational scuba-diving organizations lead to 13 areas being proposed for closure in the recreational regulation package. The package of proposed regulations stated that these areas had been suggested by divers

for two reasons. They were concerned about declines they felt had occurred in various fish populations at these sites. In addition, they were interested in unharvested areas for observation diving. The package of draft regulations also said the agency was interested in adopting several of the proposed sites as pilot areas. (Washington Department of Fish and Wildlife, 1997).

These proposals were circulated to the public and to the treaty tribes for comment. Two new sites were selected for closure, based in part on the comments received and in part on agency staff analysis. Octopus Hole (Hood Canal) and Orchard Rocks (Rich Passage near Bainbridge Island) were closed for harvest of all species. In addition, the Edmonds Underwater Park was enlarged to match the area under lease by the City of Edmonds, and two beaches in Des Moines were also closed to match local park rules. These mark the first time the agency has closed all harvest in such a marine reserve. To effect the closures, new language was added to the agency's rules denoting these areas as "conservation areas" (Washington Department of Fish and Wildlife, 1998). Regulations for complementary closures in these areas to commercial harvest were to be considered by the Commission in June 1998 (Washington Department of Fish and Wildlife, 1998d).

In addition, areas previously closed by the Department of Fish and Wildlife were reviewed by the tribes in preparation for the next revisions of the shellfish management plans. These areas were not agreed to in the initial plans although the tribes, for the most part, have avoided harvesting in them (Cahalan, 1998). This arrangement will be discussed for possible inclusion in the redrafted plans.

Conclusions

Development of a coordinated strategy for a network of marine protected areas has been underway among Washington State agencies. Research results have played a critical role in justifying such a network and in convincing the public of the potential effectiveness.

While the strategy being developed is still in draft form, it has had various "spin-offs" including development and adoption of various policies in management agencies and adoption of several small "conservation areas" (no-take sites) under Department of Fish and Wildlife recreational regulations.

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A Marine Protected Areas Strategy for the Pacific Coast of Canada

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Introduction

In 1994, the governments of Canada and British Columbia established an inter-governmental Marine Protected Areas (MPA) Working Group and a senior management Steering Committee to develop an integrated marine protected areas strategy for the Pacific coast of Canada. The agencies involved in this initiative include: the Department of Fisheries and Oceans (DFO), Parks Canada, B.C. Parks, the B.C. Land Use Coordination Office, Environment Canada (Canadian Wildlife Service) and the B.C. Ministry of Fisheries. Since fruition, these groups have been committed to working together in a coordinated effort to develop a Marine Protected Areas Strategy in full consultation with stakeholders involved in the marine environment.

The consultation process began in 1995 with the first Marine Protected Areas Forum in Cowichan Bay on Vancouver Island. This multi-stakeholder meeting brought together a wide range of people, including all three levels of government, First Nations, commercial and recreational fishers, environmental groups, scientists, and academics. During this forum, issues relating to the development of an MPA Strategy for the Pacific coast of Canada, the establishment of a network of protected areas in the marine environment, and the potential for stakeholder involvement throughout these processes were identified and discussed. In addition, government commitments were made to continue working on policy components of the MPA Strategy and to convene a second forum to discuss these policy issues.

In March 1997, the MPA Steering Committee and Working Group convened the second in a series of multi-stakeholder Marine Protected Areas Forums. In this case, two forums took place on the south and north coasts of B.C. (in Parksville and Prince Rupert, respectively) and involved greater participation from the various stakeholder groups. The purpose of these forums was to discuss the MPA Steering Committee and Working Group's draft discussion paper, "Toward a Marine Protected Areas Strategy for the Pacific Coast of Canada." This paper proposed the major policy components of an MPA Strategy for the Pacific coast, including: a common vision for and definition of MPAs; common goals and objectives for the MPA system; guiding principles for the establishment and management of MPAs; possible management regimes and designations for MPAs; and a proposed process for the identification, evaluation, establishment and management of MPAs.

The MPA Strategy is being developed to ensure that the MPA initiatives of several agencies in both Canada and B.C. are undertaken through one integrated process. The recent enactment of the Oceans Act, which shifts the Department of Fisheries and Ocean's (DFO) focus from species to ecosystem management, provides for the establishment and management of Marine Protected Areas by that agency. In addition, Parks Canada is currently pursuing new legislation to establish and manage a system of Marine Conservation Areas. Environment Canada has also expanded its role in the marine environment with amendments to the Canada Wildlife Act in 1994, enabling the Canadian Wildlife Service to establish Marine Wildlife Areas. B.C. Parks continues to expand its system of marine and coastal provincial parks and ecological reserves. The still evolving MPA Strategy is the first attempt in Canada to integrate both federal and provincial MPA programs into a single common initiative that has as its central goal the

completion of a comprehensive system of MPAs along the Pacific coast of Canada.

A Proposed Definition for Marine Protected Areas

MPAs on the Pacific coast will include legally defined areas in the intertidal, subtidal and deep ocean marine environments, and, depending on the particular designation, may include their overlying waters, the seabed and underlying subsoil, their associated flora and fauna, and historical and cultural features. These areas will be reserved by legislation to protect part or all of the enclosed environments. In some cases, for example, an MPA could protect only the seabed or only the water column, although such a scenario would be the exception rather than the rule. This definition of MPAs is intended to be as inclusive as possible, to enable the establishment of a flexible and all-encompassing system of MPAs on the Pacific coast.

By using a variety of federal and provincial designations, MPAs along the Pacific coast will utilize a range of management regimes. MPAs will range from: highly protected areas that sustain species and habitats, to areas established primarily for recreational use or cultural heritage protection, to less restrictive areas in which the conservation of species, habitats, and their associated ecosystems is coupled with recreational opportunities and other explicitly defined activities such as commercial and sport fishing.

Benefits of Marine Protected Areas

It is anticipated that the establishment of a comprehensive system of MPAs will produce a variety of benefits to society at large, including the following:

Protect Biodiversity and Ecosystem Structure, Function and Integrity

Marine protected areas can contribute to the maintenance of biodiversity at all trophic levels of the ecosystem, and protect food web relationships and ecosystem processes. Marine protected areas enable the maintenance of species presence, age and size distribution, and abundance. They prevent vulnerability and the eventual loss of species, and they preserve the natural composition of the community.

Contribute to the Conservation of Fishery Resources

Marine protected areas can protect spawning stocks, spawning stock biomass and viable spawning conditions; raise population fecundity by enhancing reproductive capacity; enhance recruitment and spill-over of adults and juveniles into surrounding waters; and serve as harvest refugia.

Provide Opportunities for Education and Research

Marine protected areas can: foster an increased understanding and awareness of marine ecosystems and marine issues; serve as scientific benchmarks; provide sites for long-term monitoring of relatively undisturbed sites and intact ecosystems; and play a valuable role in public education efforts related to the importance of marine conservation and the impacts of human activities on marine biodiversity.

Provide Recreation and Tourism Opportunities

MPAs can provide opportunities for outdoor recreation and tourism, as well as the pursuit of activities of a spiritual or aesthetic nature. The protection of special recreation features, such as boat havens and safe anchorages, beaches and marine travel routes, help secure the wealth and diversity of recreational opportunities available along the coast.

Provide Socio-Economic Benefits for Coastal Communities

MPAs can assist in and contribute to diversifying and stabilizing the economic base of coastal communities by such means as enhancing the sustainability of commercial and sport fisheries, and by providing opportunities for recreation and tourism operations and the development of local and regional support services.

A Proposed Vision for a System of Marine Protected Areas

Marine protected areas are a major component of Canada's and British Columbia's commitment to protecting and restoring the quality and integrity of the marine environment, and to securing a sound and prosperous economy for present and future generations.

Canada and British Columbia will complete a comprehensive system of marine protected areas on the Pacific coast to protect and conserve a diversity of biological, natural, and cultural heritage resources. These area will be representative of the full range of marine ecosystems of the Pacific coast, and will provide a variety of outdoor recreation and tourism opportunities.

This expanded network of marine protected areas will be established and managed through the cooperative and collaborative efforts of all levels of government, First Nations, and marine stakeholders.

Goal and Objectives of the MPA Strategy

The overall goal of the MPA Strategy is:

> Canada and British Columbia will cooperatively establish a comprehensive and integrated network of marine protected areas along the Pacific coast of Canada.

This goal will be achieved by meeting the following objectives:

To Protect Marine Biodiversity, Representative Ecosystems and Special Natural Features

Objectives:

- To protect representative examples of the marine ecosystems and habitats of the Pacific coast in order to conserve the diversity of the full range of marine species, habitats, and ecosystems; and
- To protect rare, unique, or special natural coastal and marine features.

To Protect and Conserve Fishery Resources and their Habitats

Objective:

- To assist in the maintenance of viable populations of all marine species and the sustainability of fisheries by:
    - providing harvest refugia;
    - providing a conservative tool for fisheries management;
    - protecting habitats; and
    - protecting spawning stocks.

To Protect and Present Cultural Heritage

Objectives:

- To protect and conserve sites and features of the Pacific coast's marine cultural heritage; and

- To increase the level of public awareness of human use and occupation of the marine and coastal environment.

To Provide Recreation and Tourism Opportunities

Objectives:

- To protect natural marine and coastal environments to enhance opportunities for recreation and tourism; and
- To protect special recreational features such as boat havens and safe anchorages, beaches and marine travel routes.

To Provide Opportunities for Scientific Research

- Objective: To facilitate research to increase the level of scientific knowledge about marine ecology, ecosystems and the effects of marine protected areas on marine resources.

To Provide Opportunities for Education and Increasing Marine Environmental Awareness

- Objective: To foster greater public understanding of marine ecology and conservation through education programs and stewardship initiatives.

A Variety of Objectives: A Range of Uses

The objective(s) for which an MPA is established will influence both its legal designation and the selection of appropriate uses for the area. A coast-wide system of MPAs that would collectively fulfill the above objectives would utilize the full spectrum of management regimes, defining levels of resource protection that could vary both within and among MPAs. As discussed above, these levels of protection range from strict preservation on a site-specific level at one end of the spectrum to a level aimed at multiple-use, with a broad mandate for resource conservation on an ecosystem level, at the other.

For example, areas possessing an outstanding marine feature, a critical spawning habitat for a particular species, or perhaps a historic shipwreck, may require high levels of protection. All consumptive activity, and in particularly sensitive cases, most recreational activity, may be prohibited. Such areas would most likely be established as ecological reserves under the province's Ecological Reserve Act or as Marine Protected Areas under the Oceans Act. They could also be created as preservation zones within larger, more multiple-use, MPAs such as marine conservation areas and provincial parks.

Other MPAs could be created expressly for recreation or tourism purposes, such as provincial parks under the Park Act, and certain zones within national or provincial parks or marine conservation areas. These could provide for a wider range of uses, including boating and sport fishing. Other marine protected areas will place management emphasis on the conservation of wildlife. These types of MPAs may have a less restrictive management regime that focuses restrictions on only those human activities that would compromise protection of the targeted species, features or values within the protected area. Activities and uses that do not compromise their integrity could be permitted.

The size of MPAs can also influence the range of protection levels. Relatively large MPAs may be established to protect representative marine ecosystems or large marine features such as offshore banks, the marine habitats surrounding island archipelagos or the extensive foraging areas utilized by sea birds near their colonies. Such MPAs may be able to accommodate a wide range of permitted uses and sustain a more conservative level of protection. These relatively large MPAs can integrate the objectives of conserving marine biodiversity and fisheries resources with the need for continued access to recreation opportunities, tourism and/or sustainable resource harvesting.

Minimum Protection Standards

While the levels of protection can vary along the management spectrum, there must always be a recognized minimum level of protection that applies to all MPA designations. Canada and B.C. have agreed to the following Minimum Protection Standards that would apply to all MPAs established on the Pacific coast: no ocean dumping; no dredging; and no exploration for or development of non-renewable resources. Note that these minimum standards do not apply directly to the harvest of living resources. The levels of protection that would be applied to the living resources within a particular MPA would be determined on a case-by-case basis, through the preparation of a management plan, with the involvement of First Nations, marine stakeholders and the public.

Planning a Network of Marine Protected Areas for the Pacific Coast of Canada

To effectively plan for a network of MPAs on the Pacific coast of Canada, an integrated and collaborative approach is required to ensure that the full range of resources and values present in coastal and marine areas are considered in relation to community, economic and environmental needs. To provide a context for all resource use planning, including MPAs, Canada and B.C. are developing an Integrated Coastal Zone Management (ICZM) planning approach for the coastal areas of British Columbia. This approach enables governments, stakeholders, advocacy groups, communities and individuals to collaborate in making comprehensive coastal and marine resource management decisions. ICZM plans consider the full range of resources and values present in coastal and marine areas and provide direction for their future use, as well as a mechanism for evaluating the success of management activities over time. Results are future-oriented and include monitoring and plan adjustment in response to changing societal values and circumstances.

A Regional Approach to Integrated Marine Planning

The planning and management requirements of the various coastal regions of B.C. vary significantly. The north coast, for example, is still relatively wild and pristine, with limited coastal development. In contrast, the Strait of Georgia supports the majority of British Columbia's population and faces numerous pressures from pollution, coastal development, habitat loss, increased fishing pressure, and the introduction of exotic species. For these and other regions of the coast to be planned effectively, a series of regionally based planning processes will be required. In addition, different levels of planning may be required to accommodate the needs of First Nations, stakeholders, and the general public in different regions along the coast.

Six regions are currently being considered for formulating a regional approach to planning on the Pacific Coast:

- the north coast
- the Queen Charlotte Islands
- the central coast
- the west coast of Vancouver Island
- the Strait of Georgia
- the offshore region

Canada and B.C. estimate that all regional planning processes and a comprehensive network of MPAs on the coast could be completed by the year 2010.

Planning the System of MPAs

The governments of Canada and B.C. have agreed to institute a common generic approach to planning for MPAs, within the broader context of ICZM planning, that could be applied throughout the

various regions of the coast. There would, of course, be enough flexibility built into this approach to allow for regional differences. In simple terms, this generic planning process consists of the following three phases:

- Area Identification,
- Information Gathering and Evaluation, and
- Planning and Decision Making.

The Identification Phase

The first step in establishing a system of MPAs is to identify potential MPAs that reflect the range of key marine values, attributes and features of Canada's Pacific coast. In each different planning region, community groups, First Nations, governments, stakeholders, academic institutions, individuals, and the general public will have opportunities to identify MPA candidates. The primary mechanism for MPA identification would be the various regional planning processes.

Canada and B.C. are also considering the creation of an inter-governmental Marine Protected Areas Secretariat, which could provide a "one-stop-shopping" approach for all MPA proposals for the Pacific coast. Such a body would be particularly useful for those who are not directly involved in a regional planning process but would like to identify MPA candidates in a particular region. The Secretariat's responsibilities would include: receiving and reviewing proposals, channeling proposals and any additional information to the appropriate regional planning process, and maintaining a central data base of MPA proposals. In the absence of an available planning process, the Secretariat could also investigate management options such as the application of interim management guidelines, conducting a special study or holding the proposal in abeyance until a regional planning process is available.

The Information-Gathering Phase

The purpose of the information-gathering phase is to collect data and information on proposed MPAs according to ecological, recreational and cultural heritage. Ranking or selecting MPA proposals does not occur in this phase.

This information will be collected and analysed by a technical review committee operating under the auspices of the regional planning processes. The technical review committee would consist of government representatives with a wide range of technical and scientific expertise. This committee would ensure that all available information is collected and compiled for each MPA proposal. In many cases, the technical committee would solicit input from non-government representatives. All collected information is forwarded to the participants in the regional planning processes to aid in the decision-making process.

The Planning and Decision-Making Phase

The purpose of the planning phase is to bring all marine users and interests together, including First Nations, stakeholders, and the public, to review, verify and discuss all information pertaining to an MPA proposal. This includes all ecological, recreational and cultural heritage data collected in the information-gathering phase, along with traditional and local knowledge. A feasibility and socio-economic assessment, if considered necessary, could be undertaken in the planning phase. Results from this assessment would be made available to planning tables for their consideration.

Once planning tables have collaboratively agreed on the terms for establishing a candidate MPA, recommendations would be forwarded to the appropriate federal and/or provincial legislative authorities for their consideration and approval. These recommendations could include matters relating to the suite of broad permissible uses appropriate for a given MPA and the most appropriate legislation and regulations to govern its establishment to ensure that the area can be legally managed to achieve the intended management objectives.

In the event that an MPA proposal is located within a region not undergoing regional planning,

several options may be available for making interim or longer term decisions:

- The application of Interim Management Guidelines;
- Conducting a special study; or
- Holding the MPA proposal in abeyance until a planning process is available.

Interim management guidelines. Interim management guidelines may be applied where appropriate and necessary to protect the values of the candidate MPA. There would not be a blanket moratorium on resource development opportunities or activities in these areas as marine planning processes proceed. Instead, interim management guidelines may be applied on a case-by-case basis which, where required, may restrict certain activities that might compromise the values of a MPA candidate.

Special study. In unique cases, candidate MPAs that will not be undergoing regional planning may be considered through the application of a special study. A comprehensive public consultation process would be associated with this study to ensure that all stakeholders are involved. This approach would be very limited in use and applied only in certain situations. Areas that contain unique ecological processes, critical habitat, or areas for endangered or threatened species may be examples of candidate MPAs that may, if necessary, be considered through this approach.

Holding proposals in abeyance. Candidate MPAs proposals that are not eligible for the application of interim management guidelines or a special study will be held in abeyance, in most cases, until a regional planning process is put in place.

Next Steps in the Development of an MPA Strategy for the Pacific Coast

Throughout the development of the MPA Strategy for the Pacific coast, the governments of Canada and B.C. have been, and continue to be, committed to continued consultation with First Nations groups, stakeholders and other interested parties. Upon completion of this consultation, Canada and B.C. anticipate the draft Strategy to be released in early 1998, which will be distributed widely among marine stakeholders, First Nations and the general public for yet another round of consultation. Canada and B.C. hope to be able to finalize the MPA Strategy in 1998 to mark a significant contribution to the commemoration of the International Year of the Ocean.

Authors' Note

In August 1998, the governments of Canada and British Columbia released a discussion paper entitled "Marine Protected Areas: A Strategy for Canada's Pacific Coast." The document was to be available for public review and comment for a period of 90 days, during which government representatives were also to be available for meetings to discuss the document in more detail.

Underwater Park Management

Bruce Higgins
Marine Concepts

Abstract

In a quest to protect marine resources, one available option is the creation of underwater parks. The City of Edmonds created the Edmonds Underwater Park at Bracketts Landing in 1970. This no-harvest area has not only protected marine life by city ordinance, but allows divers to see and enjoy a diverse ecosystem. The success of the park is due in part to the management plan used to operate the park. The park's 25 acres of sub-tidal and two acres of uplands can be one possible local model to evaluate a protected area that has recovered nicely from degradation.

The details of park management are explained and contrasted with a 1996 effort with the City of Seattle and a 1995–1997 effort with Washington State Parks. Strengths and weakness of the different management plans and styles provide direction to groups interested in cooperative efforts that include marine resource protection. The project's pace is described, since coordination with the marine environment can be a factor in understanding success and response. Changes in management and other City of Edmonds policies have affected the park and the health of the marine life. Only by long-term evaluation can progress be made.

Beach Monitoring and Beach Nourishment for Surf Smelt Spawn Habitat Mitigation at Lummi Indian Reservation

Jim Johannessen
Coastal Geologic Services, Inc.

Abstract

A beach-monitoring program was initiated in the fall of 1996 at the Lummi Indian Reservation, near Bellingham, Washington. Monitoring began prior to upcoming major coastal road repairs and improvements that will include more than 9,000 lineal feet of new rock revetment constructed by the Army Corps of Engineers, Seattle District. A physical monitoring program was designed to allow tribal resource managers to try to mitigate negative effects of shore armoring on existing surf smelt (*Hypomesus pretiosus*) spawn habitat, as well as on sand lance (*Ammodytes hexapterus*) spawn habitat and eel grass (*Zostera marina*) beds. A beach nourishment plan was developed to replace surf smelt spawn substrate that will no longer be provided by mass wasting and erosion of bluffs, following construction of the revetment and buttress fill, and to try to mitigate direct and indirect negative impacts caused by the revetment. A biological monitoring program was initiated prior to the physical monitoring to better understand the extent, timing, and variability of surf smelt spawning in the study area. The study area contains a gravel beach that is subjected to moderate energy wave attack during predominant southerly wind events, as well as to excessive shallow groundwater drainage through clay-rich glacial deposits. Average bluff crest retreat rates have been estimated at 4.2 inches/year.

Physical monitoring consists of biannual beach profiling and sediment sampling at 14 stations. Beach profiles are measured at the end of the summer and the end of winter using a total station theodolite. Selected profiles are also monitored following storms. Profiles are measured from monuments located below the beach surface in the narrow backshore area near the bluff toe. Sediment samples are collected from each profile at three fixed tidal elevations in the upper intertidal zone, within the potential surf smelt spawn habitat band. A portion of the sediment samples was analyzed for grain size and others were archived for possible later use. Detailed vertical sediment characterization was performed at selected profiles where spawning has occurred.

Preliminary profile results from fall 1996 and 1997 show mixed beach response along shore, erosion in several areas, and little net change elsewhere. Upper-intertidal beach sediment varied considerably. Complexities of the system studied directly affect the stability of the beach and bluff and complicate analysis. Complexities include variable bluff retreat rates that are controlled by intermittent occurrence of glacial deposits of the bluff (which influences drainage, bluff stability, and input of suitable grain size sediment to the beach), different exposure to waves, and amount and type of existing shore armoring. Weather during the winter of 1996–97 was unusually severe, with above average precipitation, an extreme runoff event caused by excessive rain on approximately 28 inches of snow, and high intensity of both southerly and northerly wind storms. While wave attack during higher high water was above average during the winter, substantial beach erosion occurred only at the area exposed to wind waves from the north. This area experienced much less mass wasting of the bluff, and therefore had much less sediment input to the beach. Monitoring will continue and results will direct future beach nourishment efforts while our understanding of the system improves. More years of data are clearly required.

7A: Protection of Marine Habitats

Questions & Answers

A: [In response to an unrecorded question:] I think the short answer to your question is yes. But I may be premature in saying that. We certainly have lots of oceanographic data, especially for the Strait of Georgia, and in conducting the work that I hope to do over the next two years, conducting a feasibility study for a proposed national marine conservation area in the southern Strait of Georgia, which is essentially equivalent to the National Marine Sanctuaries Program, we have lots of oceanographic data—current and temperature, salinity, all of that type of information—that we will use. I'm not an ocean scientist myself so we'll have to hire someone to tell us what it means, but do we want to take that holistic ecological approach to establishing a true network on an ecological basis, the answer is yes. How successful we will be, time will tell.

Mills: In terms of design, some rockfish and larvae and juveniles are in the water column for four months, and oceanographically, can we really predict where they will be four months from now? Back when I was working on oil spills, I looked at a lot of floater studies and you cant' tell where something is going to be four months later. I mean, you can tell where a preponderance would be, but I would question how well we can connect those two in design. For species that land more locally, that's a distinct possibility and should be a consideration. But I would say that to take it to that level of design, when we're actually getting down to selecting sites, may be premature. I would not be able to stand in front of a group and say, 'I need this site and this site only, not a site that's ten feet away or that's a quarter of a mile away' at the present time. I don't know that the data are behind us to say that one specific site is the site that we need. I'd say that we'll use adaptive management and that what I'd really like is a way to head-tag rockfish eggs and larvae so I can tell where they go to from these sites, because that kind of information will be critical as we move forward, as we are doing adaptive management on these sites.

Q: Is there any attempt to privatize the marine protected areas such as possibly granting a conservation easement I exchange for something like a reduced tax assessment or something. It seems that there could be an awful lot of opportunity there for setting aside property that way and it faces us with reality in terms of how much of the resource out there, in terms of tidelands and shorelines, is actually under private ownership.

Mills: Sixty percent of the tidelands in Puget Sound are privately owned, I believe that's the approximate figure. The Heritage Program under DNR, which is a land-based program, does include things like voluntary set-asides or local privately owned areas that can be designated. There is no connection to a reduction in taxes at the present time. That would have to be passed either by the legislature or by local government to give some kind of tax incentive to do that. The primary focus of marine protected areas in our work has not been the intertidal area. Most of the areas that Mike counts are intertidal, not subtidal. Our main focus has been on the subtidal areas and those at present are under the ownership of DNR.

PUGET SOUND RESEARCH '98

SESSION 7B

HARMFUL ALGAE IN PUGET SOUND-FROM RESEARCH TO MANAGEMENT

Session Chair:

Vera Trainer

National Marine Fisheries Service

Harmful Algal Blooms in Puget Sound: General Perspective

Rita A. Horner
School of Oceanography, University of Washington

Introduction

Worldwide, harmful algal blooms (HABs) are apparently spreading, occurring over longer time periods, and producing higher levels of toxin in shellfish. Western Washington is no exception.

In Puget Sound, HABs cause recurrent public health and economic problems and are related to paralytic shellfish poisoning (PSP), domoic acid poisoning (DAP), and mortalities of pen-reared salmonids. More potentially harmful phytoplankton species (about 20) are present in western Washington waters than in other U.S. coastal regions. The organisms that produce the toxins are common members of the phytoplankton community in Puget Sound, but little is known about their distribution, abundance, and physiological ecology.

Toxins In Shellfish

Paralytic Shellfish Poisoning (PSP)

PSP is the best known of the toxin syndromes produced by HABs and is what most people mean when they say or hear the term "red tide." The earliest recorded PSP incident occurred in 1793 when four members of Captain George Vancouver's crew became ill and one died after eating mussels harvested from Poison Cove in central British Columbia. Other deaths have occurred in British Columbia, the most recent in 1980 (Taylor and Horner, 1994). In Washington, the most recent deaths occurred in 1942 when three people died after eating PSP-contaminated mussels and clams harvested from the Strait of Juan de Fuca. High levels of PSP were found also in razor clams on the open coast near Willapa Bay (Nishitani and Chew, 1988). At that time, the management decision by the Washington Department of Health was to impose a harvest closure on all bivalve molluscs (except razor clams) from Dungeness Spit to the mouth of the Columbia River for the period 1 April–31 October. Razor clams were exempt because PSP toxin is concentrated in the digestive gland, which is removed before eating. The closure has been in effect every year since 1942.

Shellfish harvest closures are in effect also at many sites within Puget Sound during the summer and fall. In Puget Sound, no illnesses were reported from south of Admiralty Inlet before 1978. In the fall of 1978, however, high toxicity (up to 30,000 µg toxin per 100 g shellfish tissue) spread from Whidbey Basin south to Des Moines with low levels (< than 80 µg which is the harvest closure level) occurring at the Tacoma Narrows in 1979. No closures occurred in south Puget Sound until 1988 when oysters harvested from Carr Inlet were found to be toxic (up to 2000 µg) and commercial product was recalled. In 1991, Case Inlet was closed for the first time (Matter, 1994). Widespread closures occurred throughout south Puget Sound in the late fall of 1997 (see F. Cox, this volume).

A causative organism was not linked to an illness or fatality in the Pacific Northwest until 1965 (Prakash and Taylor, 1966). It is now known that members of the dinoflagellate genus *Alexandrium* (previously called *Gonyaulax* and *Protogonyaulax*) cause PSP and at least five known toxin-producing species are present in Northwest waters. These dinoflagellates occur as single cells or in chains and are able to swim, often occurring in surface waters during the day and at depth during the night. They rarely produce visible blooms.

Domoic Acid Poisoning (DAP)

Domoic acid has been found in razor clams on the Washington coast in some years since 1991, sometimes necessitating closure of the recreational razor clam harvest. It has not been a problem in Puget Sound, although blooms of the causative organism have been reported from Hood Canal

(Horner et al., 1995) and Penn Cove (R. Horner, unpubl. obs.; V. Trainer, this volume), and low numbers of cells are regularly seen in water samples collected from throughout the Sound.

This syndrome, also known as amnesic shellfish poisoning (ASP), is caused by several species in the diatom genus *Pseudo-nitzschia*. Blooms of these species may be long-lived, lasting a month or more (e.g., Hood Canal in 1995, Penn Cove in 1997), or they may be very short, lasting only a few days (e.g., Port Angeles in 1992; Grayland in 1997). The cells are long and needle-shaped and occur in chains held together by the overlapping ends of adjacent cells.

Mortalities of Finfish

Deaths of salmonids held in net pens have been known in Puget Sound at least since 1976 (Rensel et al., 1989) with major losses occurring in 1987, 1988, 1989, 1990, and 1997. HABs threaten not only current production of fish, but in the past have also been considered serious risks related to site development for new public and private net-pen facilities. The fish-killing organisms are not known to cause illness in humans.

Fish mortalities are caused by two quite different organisms. The one that receives the most attention in the press is a small, brown, flagellated organism called *Heterosigma akashiwo* that may form tremendous, visible blooms covering wide areas (see L. Connell, this volume). No specific toxin has been identified to date. The other organism includes several species of the diatom genus *Chaetoceros* that have long, barbed spines that get trapped between the gill filaments of the fish and cause excessive mucus production and eventually suffocation (Rensel, 1992). This is a physical mechanism and no toxin is produced. Visible blooms are usually not produced and as few as 5000 cells/L can cause fish deaths.

Current Knowledge

Most of our information on HABs in Puget Sound waters is based on toxins in shellfish rather than on the biology of the causative organisms. Reference will often be made to "blooms of toxic organisms" when what is meant is that toxin levels in shellfish are high. In fact, most often when toxin levels in shellfish are high, no bloom is obvious. High toxin levels may be produced by low numbers of cells, or blooms may be subsurface and not readily seen. Moreover, there may be blooms of potentially harmful species and no toxins are produced. In Puget Sound, the most spectacular discolored water is usually caused by two harmless species. Most of the time blooms are discovered only when shellfish become toxic or finfish die. Then we assume a bloom occurred, but cannot always determine where the bloom started, what environmental conditions were present when the bloom was initiated, or what conditions were necessary for toxin production. Information on the basic biology of HAB species is gradually accumulating based on field and laboratory investigations that eventually may allow better predictive capabilities in the future.

Management Strategies

Because it is rarely possible to predict when and where HABs will occur in Puget Sound, resource managers often have little warning about the presence of toxins and must close both commercial and recreational harvest areas with little notice. The closures are often widespread and may have severe economic impacts on local communities dependent on shellfisheries. Knowledge of the spatial and temporal distribution of HAB species would help alleviate this problem. As a result, phytoplankton monitoring is used at some finfish and shellfish farm sites. This is a quick, easy, but often time-consuming, way to determine if harmful species are present so that preventive measures can be taken to keep finfish alive or have shellfish tested more frequently. The availability of simple, inexpensive, accurate immunochemical probes that change color when put in sea water containing HAB species would be an ideal solution for growers, recreational harvesters, and resource managers, but their development is still in the future.

In addition to the sporadic occurrence of HABs, other factors contribute to the management

problem. The toxins give no indication of their presence, cannot be destroyed by cooking or freezing, and there are no antidotes. They are very potent, thus the ability to detect them at low concentrations is critical. By the very nature of the toxins, it is difficult to design suitable detection methods. For example, PSP is not caused by one toxin, but by a suite of about 20 toxins, some of which change their structure within some shellfish. Further, depuration of toxins from shellfish may be rapid (e.g., domoic acid from mussels), or very slow (e.g., domoic acid from razor clams or PSP from butter clams). Numerous methods have been tried to increase the depuration rate, including moving toxic shellfish to areas where there is no toxin. Unfortunately, this may only increase the problem if toxin-producing cells or cysts are transferred to the clean areas with the toxic shellfish. HAB species frequently occur with harmless species and there are no measures to control or eliminate toxic species from natural phytoplankton populations. A parasitic dinoflagellate, Amoebophrya ceratii, sometimes attacks Alexandrium spp. and was thought to be a possible control (Nishitani et al., 1985), but it is not species-specific and also attacks non-HAB species.

HABs are expensive. Economic impacts may include adverse health effects, lost and/or delayed sales of product, lower prices, lost jobs, bankruptcies, less investment in aquaculture, and lost marine recreational opportunities. The 1991 domoic acid incident on the Washington coast cost local communities dependent on the recreational razor clam harvest or the commercial crab fishery between $15 and $20 million (T. Nosho, pers. comm., 1994). Included in this amount were losses of commercial oyster sales because the public feared that oysters were also toxic when they were not, the so-called "halo effect." Costs of other blooms include $4–5 million per event for *Heterosigma*-caused fish kills and $0.5 million for *Chaetoceros*-caused mortalities. The Washington Department of Health's shellfish monitoring program costs about $0.5 million per year (WDH, pers. comm., 1997).

It is obvious that HABs are, and will continue to be, a serious economic and health problem in western Washington waters. As a result of the Washington Department of Health's toxin-testing program, there have been few confirmed illnesses from commercially harvested (testing began in 1957) or recreationally harvested (monitoring started at some sites in the 1970s) shellfish. However, as toxins spread to new areas and the harvest of non-traditional invertebrate species, e.g., moon snails, shore crabs, and barnacles, increases, more people will be at risk. Consequently, changes in management strategies may be required in order to provide adequate protection to the public.

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PSP Bloom of Late Fall 1997

Frank Cox
Washington State Department of Health

The DOH Program

The Office of Shellfish Programs, in the Washington State Department of Health has a Marine Biotoxin Monitoring Program that monitors for paralytic shellfish poisoning (PSP) and amnesic shellfish poisoning (ASP) (or domoic acid poisoning [DAP]). PSP represents a significant threat to public health. The symptoms of PSP, which can begin within 30 minutes, are:

- Tingling of the lips and tongue;
- Numbness of the arms, legs, and neck;
- General muscular incoordination;
- Dizziness, weakness, drowsiness, and incoherence;
- Headache, rapid pulse, and respiratory distress;
- Vomiting, diarrhea, and abdominal pain;
- Muscular paralysis; and
- Death.

South Puget Sound PSP Bloom

Case Inlet

In the late fall of 1997, a significant PSP bloom occurred in south Puget Sound. The bloom, which began in northern Case Inlet, was first detected in a blue mussel (*Mytilus edulis*) sample, collected on October 21, 1997, from the Port dock at the town of Allyn, (<38 μg of toxin per 100 g of shellfish tissue). On November 4, 1997, the toxin level had increased to 92 μg/100g and Case Inlet south to Stretch Island was closed for commercial and recreational shellfish harvesting. Case Inlet had experienced several blooms in recent years prior to 1997, with the highest toxin levels approaching 800 μg/100g in early December 1991. By December 1, 1997, the toxin level at Allyn had risen to 6799 μg/100g, closing the rest of Case Inlet. This was the highest level recorded in Washington since the record Whidbey Island bloom of 1978, where toxin levels reached 30,000 μg/100g.

Other Areas in the South Sound

By December 1st 1997, PSP had extended into other, previously unaffected areas of South Puget Sound, requiring additional sport shellfish harvesting closures for all the waters around Harstine and Squaxin Islands in Mason County, and all the waters in Thurston County. Additionally, all the Pierce County waters south of the Narrows Bridge were closed.

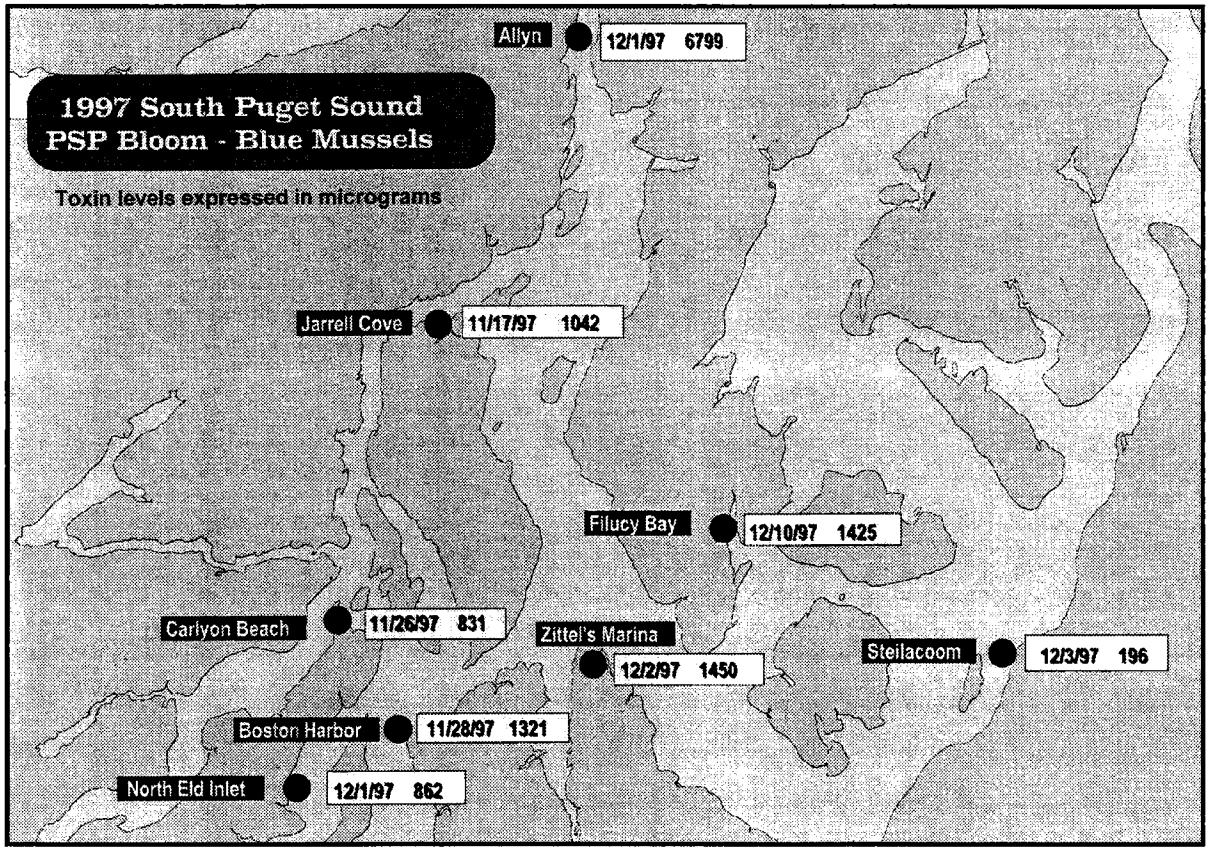

Figure 1. PSP in south Puget Sound blue mussels.

South Puget Sound Commercial Closures

Commercial closures included Case Inlet, Filucy Bay, Burley Lagoon, Pickering and Peale Passages and North Eld Inlet. There were 36 commercial companies with tidelands in the closed areas that were impacted and 11 more in South Eld Inlet that were impacted to a lesser degree. Other areas such as Totten Inlet, Hammersley Inlet, and Oakland Bay had detectable levels of toxin, but were not closed. In response to the detected toxin, many commercial companies in the open areas adjacent to the toxic areas were required to submit a large number of samples of shellfish during the bloom. The species of shellfish under commercial cultivation that were impacted included blue mussels, manila and native Littleneck clams, Pacific and European flat oysters, and geoduck clams.

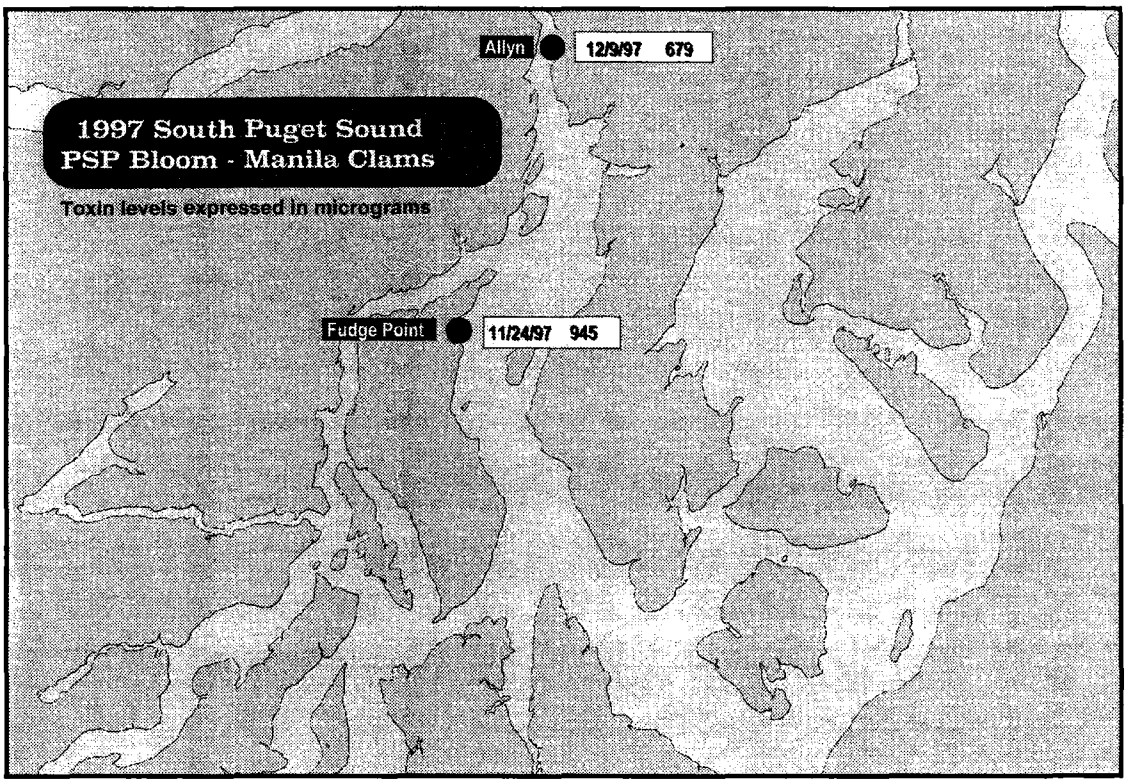

Figure 2. 1997 south Puget Sound PSP bloom in manila clams.

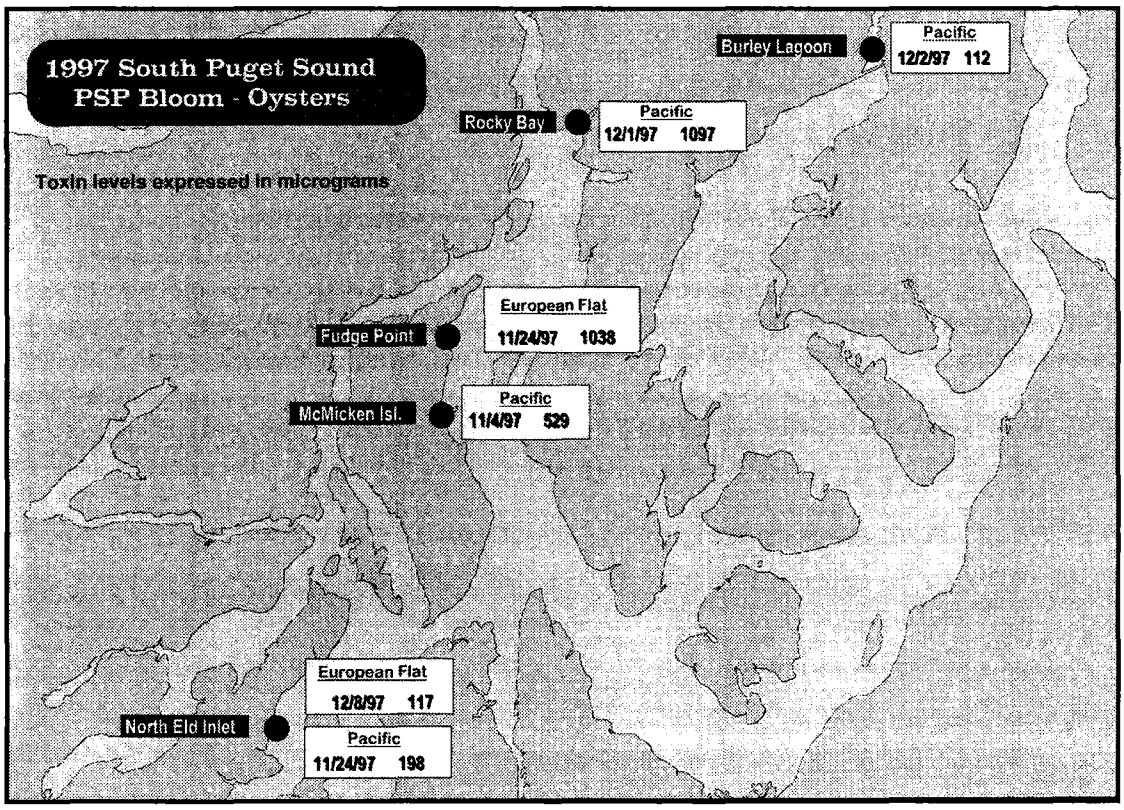

Figure 3. 1997 south Puget Sound PSP bloom in oysters.

Recalls and Illness

There was only one shipment of shellfish that had to be recalled during this bloom event. That shipment was still in transit at the time of the recall, so the toxic shellfish never reached the market. No other toxic shellfish reached the market. There were no reported illnesses associated with the 1997 fall PSP bloom.

Unusual PSP Bloom

There were three unusual aspects of this bloom: first, the late time of year of the occurrence; second, the areas involved; and third, the high level of toxin recorded. All together, there were seven sample locations in south Puget Sound that exceeded 1,000 μg/100g of PSP toxin.

Causes and Other Blooms

The unusually mild, September-like, calm, sunny weather may have played an important part in the timing of this bloom. Other locations in north Puget Sound, such as Sequim Bay in Clallam County, Discovery Bay in Jefferson County, and Birch Bay in Whatcom County, also experienced blooms at about the same time as the south Sound bloom. However, unlike south Puget Sound, these blooms did not reach very high levels of toxin and were brief in duration. The late timing of these other blooms was also most unusual.

Coastal Blooms

There were two other areas that experienced PSP blooms in November of 1997, Grays Harbor and Willapa Bay. Even though they are not part of Puget Sound, the coastal blooms are noteworthy. They were very significant and had a larger overall economic impact to the shellfish industry of Washington. The timing of all of the late fall blooms was unfortunate as they occurred right before Thanksgiving, which is the busiest time of the year for the oyster industry.

Grays Harbor Bloom

The bloom in Grays Harbor was first detected in California or sea mussels (*Mytilus californianus)* on October 29, 1997, which had a toxin level of <38 μg/100g. By November 12, 1997, the toxin had risen to 86 μg/100g. Consequently, the seven commercial companies operating in the harbor were switched to a lot-testing plan and the harbor was closed for recreational shellfishing. If a commercial bed tested at levels of 80 μg/100g or higher, it was closed. To reopen, a bed needed two samples below 80 μg/100g, collected between seven and 10 days apart. The bloom peaked around November 20, 1997, when the highest toxin level (286 μg/100g), which was in Pacific oysters (*Crassostrea gigas)* from Elk River, was recorded. By December 2, 1997, all the commercial shellfish beds were reopened. The rain storm in mid-November may have flushed the bloom out of the harbor.

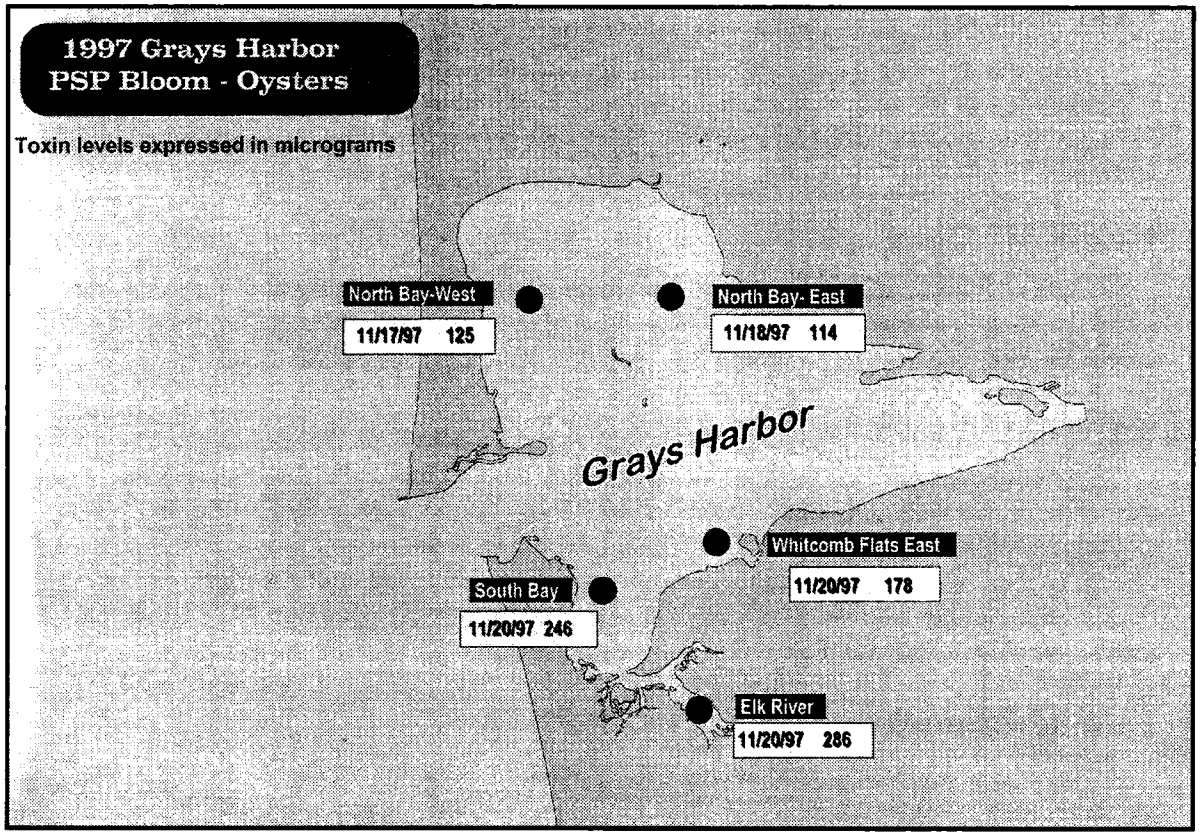

Figure 4. PSP in Grays Harbor.

Willapa Bay Bloom

The Willapa Bay bloom was first detected in California mussels and Pacific oysters on November 10, 1997 at 39 µg/100g and <38 µg/100g, respectively. By November 13, 1997, the toxin level in the oysters reached 130 µg/100g, which triggered the same actions as those taken in Grays Harbor the day before. There were 27 companies affected by the bloom in Willapa Bay. The bloom peaked around November 20, 1997, when the highest toxin level (341 µg/100g), which was in Pacific oysters from the Bruceport Area, as recorded (Figure 5). All the commercial beds were reopened by December 17, 1997. The recreational closures for both coastal harbors were lifted on January 8, 1998. As in Grays Harbor, the rain storm in mid-November may have flushed the bloom out of Willapa Bay.

Outer Coast

During the time the blooms were occurring in the coastal harbors, a recreational razor clam (*Siliqua patula)* harvest was ongoing at Twin Harbors, the ocean beach between the mouth of Grays Harbor and Willapa Bay, in front of the town of Grayland. Consequently, the razor clams were being sampled and tested for PSP toxin. The razor clams never registered a detectable level of PSP toxin. This was a major departure from the historical record, which indicated that the razor clams normally became toxic before the shellfish inside the harbors registered toxin. The only location on the outside coast where PSP was detected was at Second Beach in Olympic National Park, which is just south of the Quillayute River. At that location, California mussels registered 832 µg/100g of toxin on November 15, 1997. This roughly coincides with the peak of the harbor blooms.

The PSP blooms of the late fall of 1997 were potentially disastrous. The cooperation between the shellfish industry and the staffs of the DOH Shellfish Program and the DOH Laboratory, which occurred in the face of a common threat, made it possible to protect public health and minimize the impact to the industry. Without that cooperation, the outcome could have been very different.

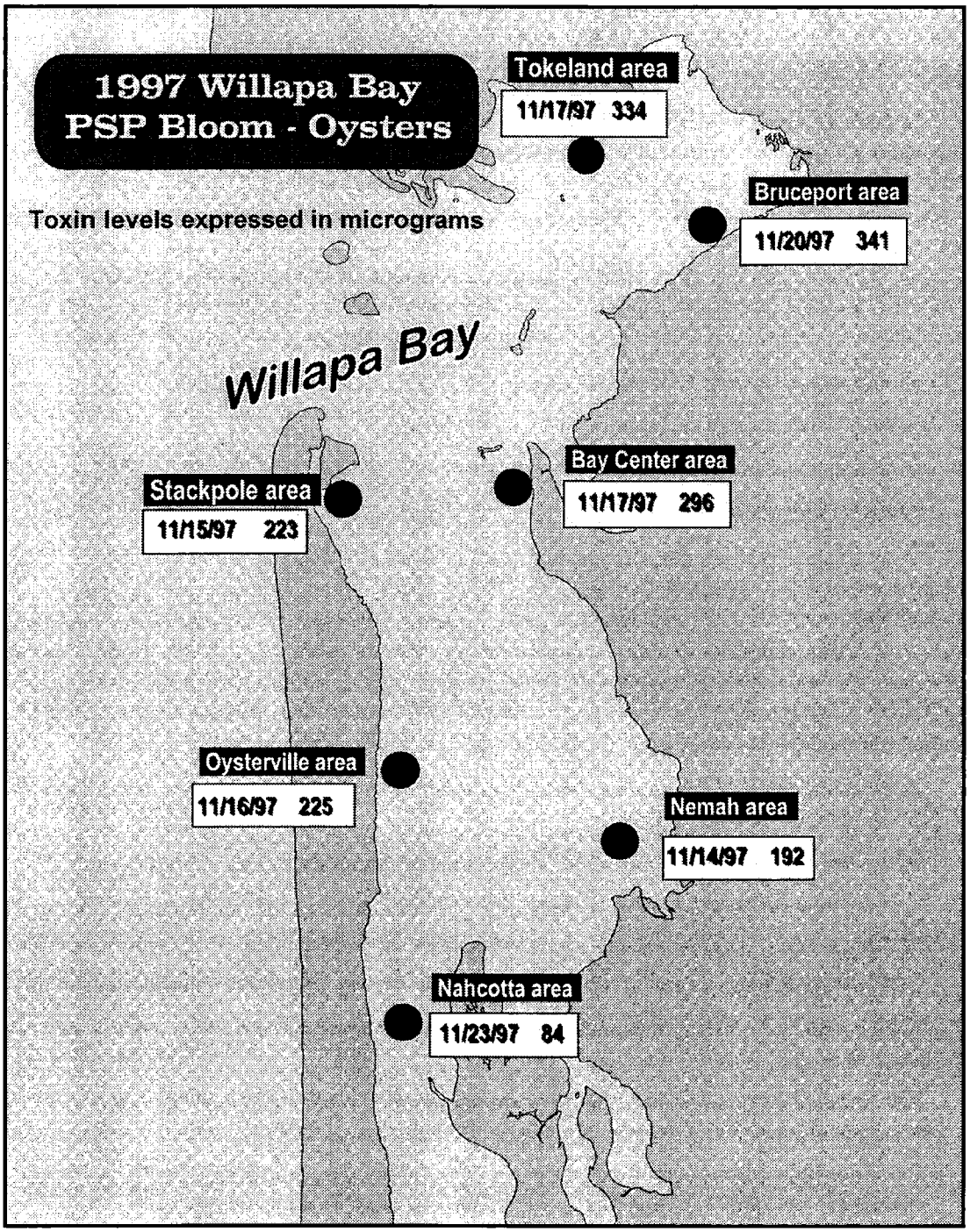

Figure 5. 1997 PSP in Willapa Bay.

Toxicity of Paralytic Shellfish Poisoning (PSP) in the Geoduck Clam

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Introduction

Paralytic shellfish poisoning (PSP) has a long history of causing major problems for shellfish consumers all over the world. (Bricelj and Shumway, 1996; Jellet, 1993; Shumway, 1989; Shumway, 1990; Neal, 1967; Sribhibhadh, 1963). Public health becomes threatened because serious illness or death can occur when toxic shellfish are consumed. Industry also becomes threatened owing to the closure of shellfish harvesting grounds, depressed markets due to loss of consumer confidence in the shellfish products, and loss of income. At present, the most effective and powerful tools available to regulatory agencies, harvesters, producers, and sellers of shellfish products in the battle against PSP are monitoring programs. In most cases, these programs effectively accomplish the following:

- minimize the threat of PSP to consumers;
- prevent product recall and minimize economic losses;
- minimize waste and protect the resource; and
- minimize harvest disruption.

In the state of Washington, the geoduck clam (*Panope abrupta*) is a valuable economic resource, valued between $3–7 million dollars annually (Figure 1; J. Markert, Washington Department of Natural Resources, pers. comm.). Recently, new, large markets have developed domestically and overseas in Hong Kong, Japan, and Singapore, where consumers often pay $12/lb or more for whole live clams. However, geoducks have been found to filter and accumulate certain algae that produce PSP toxins naturally, therefore increasing the risk of PSP to consumers. Until very recently, PSP toxicity levels in geoducks were not considered a risk to public health for various reasons:

- The viscera, typically the area for toxin accumulation in many bivalves, were assumed to be discarded prior to consumption.
- Harvesting for geoducks occurred in "PSP-free" areas of southern Puget Sound.
- Low demand for geoduck meat resulted in little pressure to increase the number of harvestable tracts.

Now, there are new causes for concern for the Washington Department of Health (WDOH):

- The visceral ball is being consumed by some members of tribal and overseas communities, who use it in soup.
- The demand for geoduck meat has skyrocketed recently, resulting in new tribal and state commercial tracts being opened in historical PSP areas of central and northern Puget Sound.
- Toxic algal blooms are extending into the previously benign areas of southern Puget Sound, resulting in previously unseen PSP toxicity in geoducks in those locations.
- Many thousands of dollars worth of geoducks are not being harvested due to concerns about PSP toxicity.
- Unfortunately, no previous information exists regarding PSP toxicity in geoducks. Variability in toxicity and anatomical distribution of toxins are unknown. Without such information, it is difficult to assess the effectiveness of the current geoduck monitoring program in protecting public health.

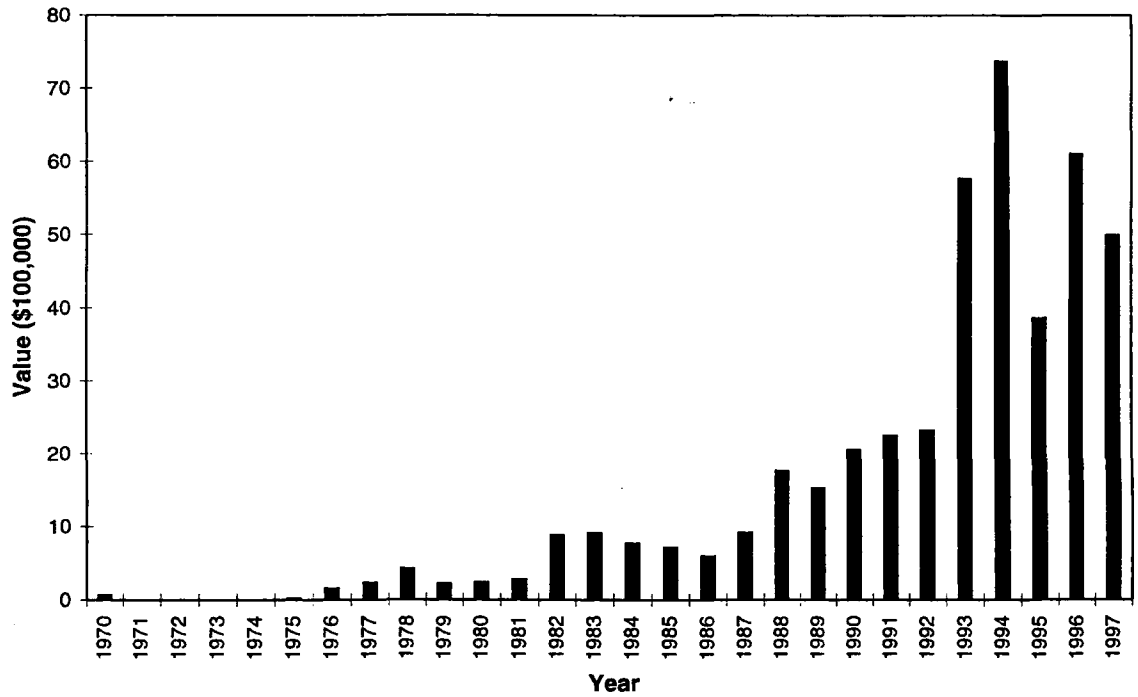

Figure 1. Annual revenue for the Washington State geoduck fishery.

Main Questions

The purpose of this study is to address the following questions:

- What is the variability in toxicity? How does toxin variability change among populations of geoducks, or among seasons?
- What is the anatomical distribution of PSP toxins?
- How should the current geoduck PSP monitoring program be modified to better protect public health?
- How do the mouse bioassay and the receptor binding assay compare in testing for PSP? Currently the mouse bioassay is the only approved method for PSP testing. The receptor-binding assay has advantages over the mouse bioassay in that it uses no live animals, is significantly less expensive, and is a high-capacity test (Doucette et al., 1997).

Methods

From June through October 1997, geoducks were collected from Quartermaster Harbor (QH), Puget Sound, by a dive team from the Puyallup Tribe. From August 1997 through January 1998, geoducks were collected near Agate Pass (AP), Puget Sound, by a dive team from the Washington Department of Natural Resources (WDNR). Within each tract, a shallow location (18 ft) and a deep location (50 ft) were selected, and all subsequent samples came from those locations. Biweekly, 10 geoducks were collected from each sampling location (20 total from each tract), along with data on substrate type, bottom temperature, whole wet weight, and shell length. Blue mussels (*Mytilus edulis*), which were also collected in Agate Pass from a lantern net suspended above the collection areas, were used as a sentinel species. After collection, geoducks were individually numbered and dissected into individual tissues: neck, mantle, visceral ball, and gill. Each tissue sample was analyzed separately for PSP toxins using the standard mouse bioassay (AOAC, 1984; Adams and Miescier,

1980; M. A. Kirkpatrick, WDOH, pers. comm.). The same results will be analyzed using the receptor-binding assay, and the results will be compared with the mouse bioassay results.

Results

Toxicity levels in geoducks from Quartermaster Harbor can be seen in Figure 2. In the deep location, variability in toxicity was low, with a pooled standard deviation (SD) of 17 g toxin, and did not change over the season. In the shallow location, variability was significantly higher, with a pooled SD of 148 g toxin, and was irregular and unpredictable throughout the study. Mean toxicity level was not increasing or decreasing, and was unpredictable as well.

Toxicity levels in geoducks from Agate Pass can be seen in Figures 3 and 4. Blue mussels do not appear to show any correlation with geoduck toxicity. Statistically, variability did not change over the season for either the deep or shallow locations, with pooled SDs of 115 g toxin and 271 g toxin, respectively. Harvest depth had an effect on variability 55% of the time. For example, there was a significant difference between the deep and shallow Agate Pass areas on August 19th, October 14th, October 28th, December 10th, December 23rd, and January 20th. In addition, harvest depth had an effect on mean toxicity level 45% of the time. For example, there was a significant difference between the deep and shallow Agate Pass areas on August 19th, September 2nd, October 7th, December 10th, and December 23rd. In summary, differences between the deep and shallow areas were not predictable in terms of mean toxin level or seasonal variability. This is in contrast to Quartermaster Harbor, where the deep and shallow areas differed significantly throughout the study period.

Overall, variability found in the shallow location of AP was approximately twice that found in QH. The variability found in the deep location of AP was approximately six times that found in QH. There was no correlation between geoduck weight and toxicity in either tract. Toxicities in each of the tissues can be seen in Figure 5, which shows that toxins appear to be isolated to the visceral ball.

Preliminary Conclusions and Implications

1. Currently, the WDOH uses a sample of three geoducks for PSP monitoring purposes. This does not appear to be sufficient, given the range of toxicities seen in the study areas. The WDOH may need to revise current sampling methods in order to better protect public health, to minimize product recall, and to minimize economic losses.

2. It may be necessary to issue a warning to consumers stating that the toxins are isolated to the visceral ball, and should be discarded prior to consumption since the market demand is for whole geoducks.

3. Overall, variability and mean toxin levels appeared to be lower in the deeper areas of a harvest tract. Perhaps harvest should be limited to certain depths during the PSP season.

4. Harvest tracts appear to behave differently in terms of mean toxin levels, seasonal highs and lows in toxicity, and seasonal variability. Each tract may have to be treated individually when sampling geoducks for PSP monitoring.

5. Currently, several monitoring programs around the world use mussels as an "early-warning species" for PSP toxicity in bivalves. Since no correlation between mussel and geoduck toxicity is apparent, blue mussels might not be effective as a sentinel species in monitoring for PSP in geoducks.

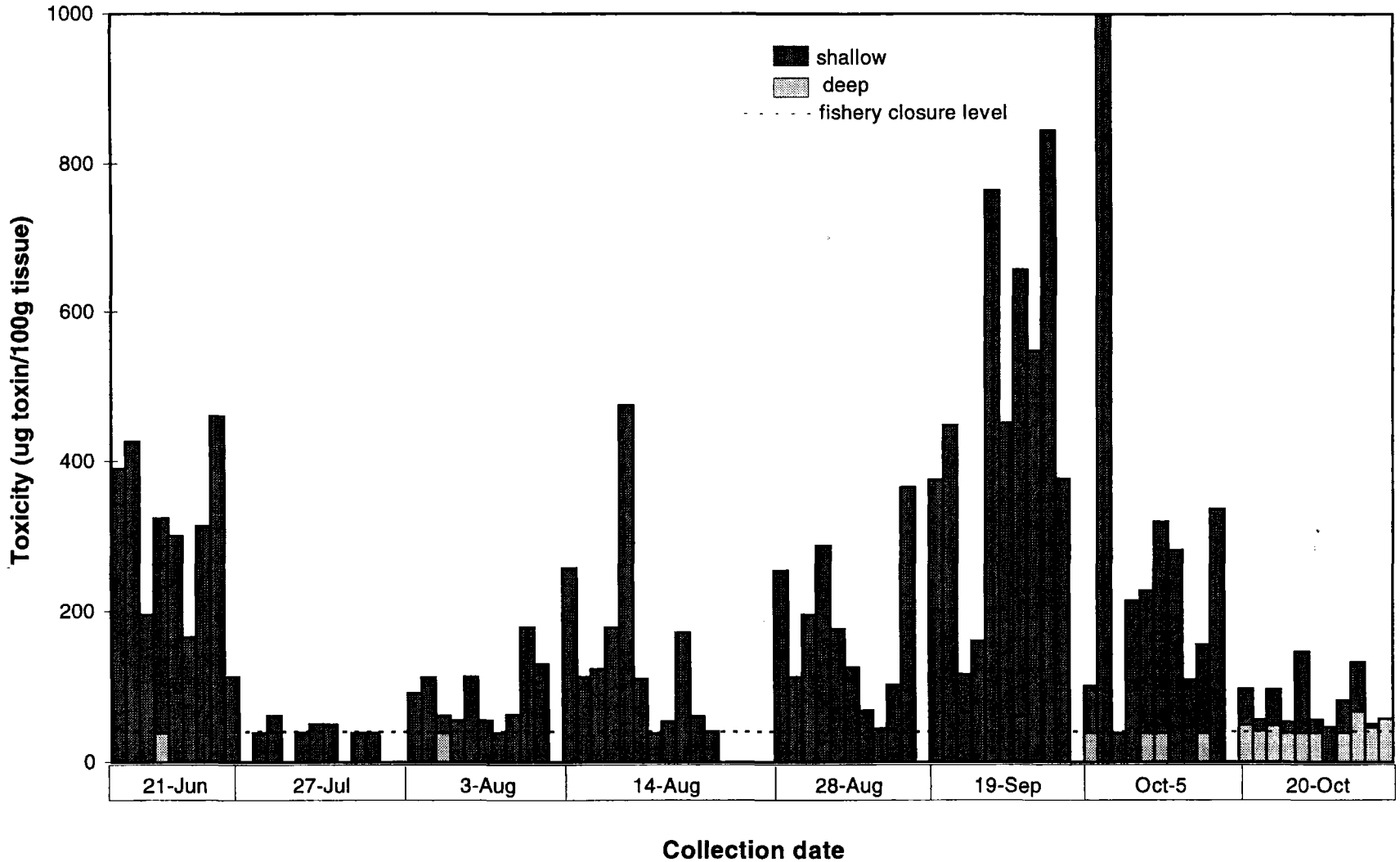

Figure 2. Toxicity levels in individual Quatermaster Harbor geoducks, June–October 1997.

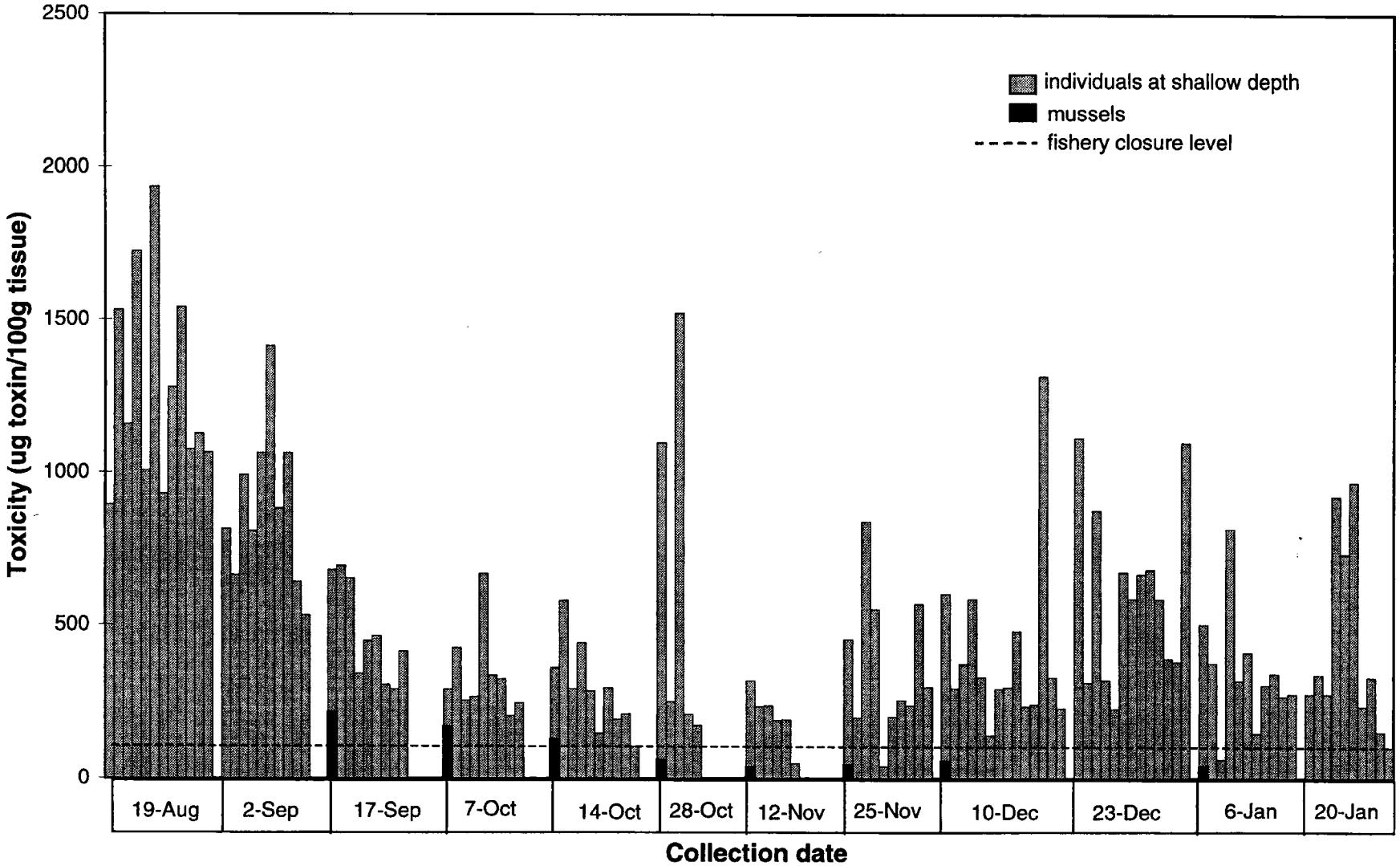

Figure 3. Toxicity levels in individual geoducks from the shallow area of Agate Pass, August 1997.

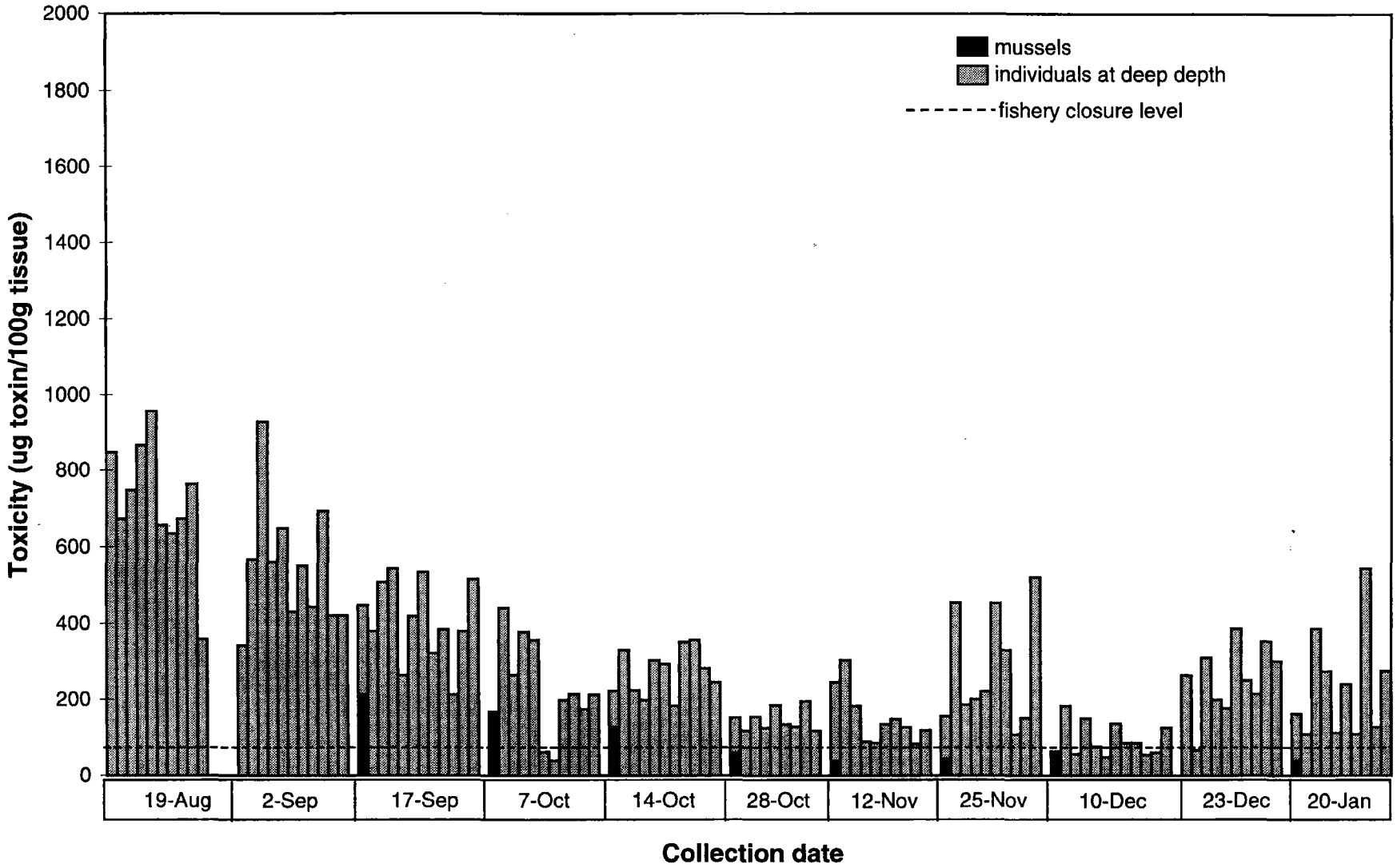

Figure 4. Toxicity levels in individual geoducks from the deep area of Agate Pass, August 1997

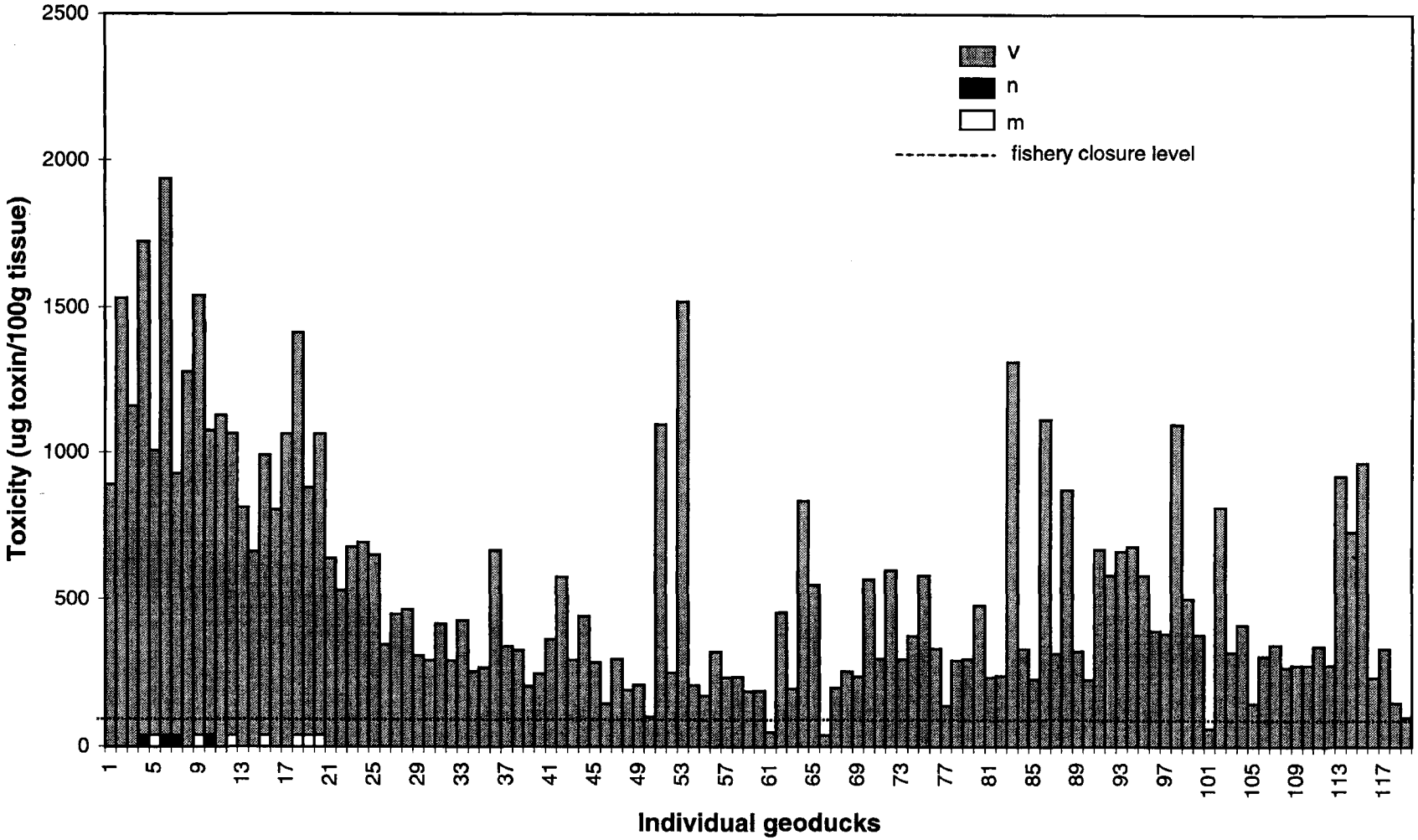

Figure 5. Toxicity levels in each of the dissected tissues: neck (n), mantle (m), and viscera (v). Data are from individual geoducks in the shallow Agate Pass collection area, August 1997–January 1998.

Acknowledgments

I appreciate Drs. Ken Chew and Sandra Shumway for leading me to this important and exciting research. WDOH and WDNR provided administrative and technical support, lab space, training for mouse bioassay procedures, personnel, supplies, and geoduck fishery information. Geoducks, divers, boat operators, and boat time were provided by the WDNR and Puyallup Tribe. John Hurst and Jack Wekell provided technical support regarding mouse bioassay procedures and/or statistical advice. Lantern nets were provided by Westcott Bay Seafarms. Funding for this research was provided by the Washington Sea Grant program, WDNR, the Tulalip Tribe, and WDOH. Salaries and tuition were provided by the Victor and Tamara Loosanoff Endowed Fellowship.

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Numerical Circulation Modeling as a Tool for Harmful Algae Bloom Research and Prediction

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Introduction

In this paper, I discuss the use of three-dimensional (3-D) numerical circulation modeling for studies of Harmful Algae Blooms (HABs). Puget Sound is being modeled this way as part of the Puget Sound Regional Synthesis Model (PRISM) at the University of Washington (UW). I will show some early model results, concentrating on the salinity field, and discuss model capabilities in relation to factors important to blooms. While true bloom prediction may be more than a decade in the future, a better understanding of what forces near-surface temperature, stratification, and horizontal stirring in the Sound is a reasonable near-term goal. Observational data collected by bloom researchers will be crucial to this effort.

Circulation Modeling

The PRISM Project

PRISM is a multi-disciplinary project, funded internally by the University of Washington, to coordinate and synthesize research, education, and outreach on issues affecting the Puget Sound basin (land, air, water, etc.). Related talks at this conference are being given by J. Richey and M. Kawase.

Puget Sound Circulation Modeling

Mitsuhiro Kawase, also a UW physical oceanographer, has initiated the circulation modeling. The Princeton Ocean Model (POM) is used, as it is by many coastal end estuarine researchers around the world. This time-dependent 3-D model allows realistic bathymetry and has a turbulent mixing parameterization. The initial simulations span more than a year of model time, and were forced by tide height at Admiralty Inlet and freshwater inflow from eight rivers, using stream flow data for October 1990–1991. Future simulations will include realistic wind stress and surface heating, available from a predictive model being run at UW Atmospheric Sciences. Ocean inflow properties from the Strait of Juan de Fuca will remain unknown until a monitoring-buoy array is set up there.

The ability to model 3-D circulation in estuaries is a recent development in Physical Oceanography. In the past, physical lab models were the only way to approach system-wide questions. Such physical models range from the three-meter Puget Sound model at UW to much larger models of San Francisco, Chesapeake, and other bays, which fill large buildings.

Model Results

The model surface salinity field during a spring tide, after a period of strong river runoff, is shown in Figure 1. Note the gradual decrease of salinity from head to mouth, most pronounced near rivers, especially the Skagit. The model horizontal resolution is 600 m (E/W) by 900 m (N/S). The year-long cycle of Skagit inflow used by the model is shown in Figure 2. It may also be seen in Figure 1 that Admiralty Inlet and Tacoma Narrows are sites of vertical mixing, bringing up saltier water from depth (Seim and Gregg, 1991, 1994). Vertical profiles of salinity from Whidbey Basin are shown in Figure 3 for times of low and high river flow. The model makes calculations on 12 vertical levels distributed evenly over the local water depth. This strategy gives greater vertical resolution in shallow areas. Comparing to analogous profiles (not shown here) from the Washington State Department. of Ecology

1993–1994 (Newton et al., 1997) an obvious feature missing is the mixed layer near the surface. This is the result of the lack of wind forcing, which promotes mixing in the top few meters of the water column (Price et al., 1986).

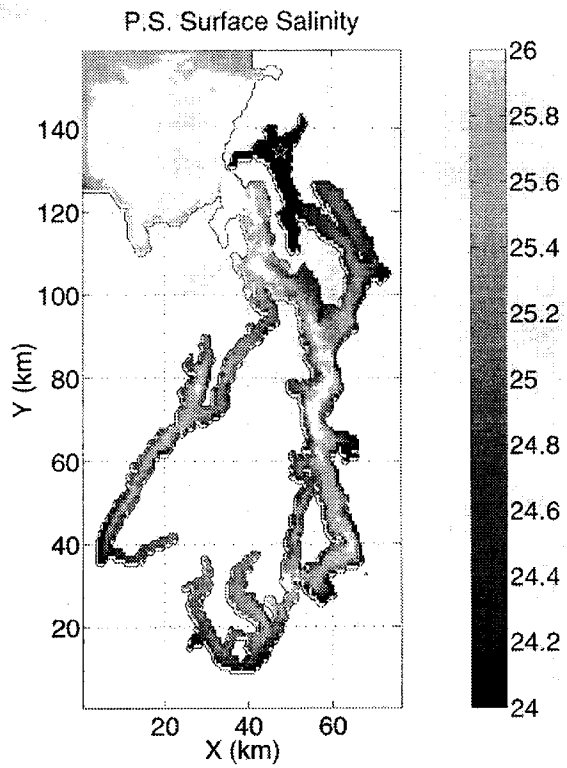

Figure 1. Model surface salinity after a time of high runoff (time shown as a star in Figure 2).

Bloom Scales and Model Scales

HABs require specific (and often not well known) conditions to occur (Steidinger, 1975; Anderson, 1997), relating to pre-conditioning, temperature, nutrients, etc. Circulation patterns such as internal waves, gravity currents, fronts, and tidal stirring can transport and concentrate the algae (Franks 1992, 1997). For *Heterosigma* in Puget Sound, certain temperature and stratification values appear to be key (Laurie Connell, pers. comm., and this volume). Using Connell's bloom observations in Rich Passage (just S. of Bainbridge Island) on July 17, 1997 as a benchmark, we may propose scales at which the model must be able to make predictions:

1) HAB inception may require water warmer than a certain (strain specific) level; model temperature predictions should be within 1 _C in the mixed layer.
2) Optimum mixed layer depth for bloom maintenance appeared to be 7–10 m, so one needs vertical model resolution of at least one meter in the euphotic zone.
3) Blooms may occur over time scales of a day, so resolution of the tidal cycle is necessary (this is essential to the estimation of turbulent mixing as well).
4) Horizontal advection can readily move bloom patches over the tidal excursion in a single tidal cycle. For fish growers, the presence of bloom conditions at a pen location becomes important in a few hours.

Implications

The PRISM circulation modeling effort should be able to give realistic stratification, temperature, and tidal-eddy advection fields in the near future, at the coarse resolution of the results presented above. Finer-scale features, such as individual bays, will require nested modeling. While the model should be able to give statistically realistic results, predictions of fields on individual days is a much harder task. Significant work will be to (1) include atmospheric forcing, and (2) make comparisons with the statistics and patterns of historical hydrographic data, especially that from Ecology's Ambient Monitoring program. Correlation of river flow, weather, and tidal stage with stratification events may be of use to growers. Because of the importance of atmospheric forcing, it will remain impossible to predict water surface conditions any farther into the future than the weather (2–5 days). Future work will involve nutrient balances and eventually algae modeling.

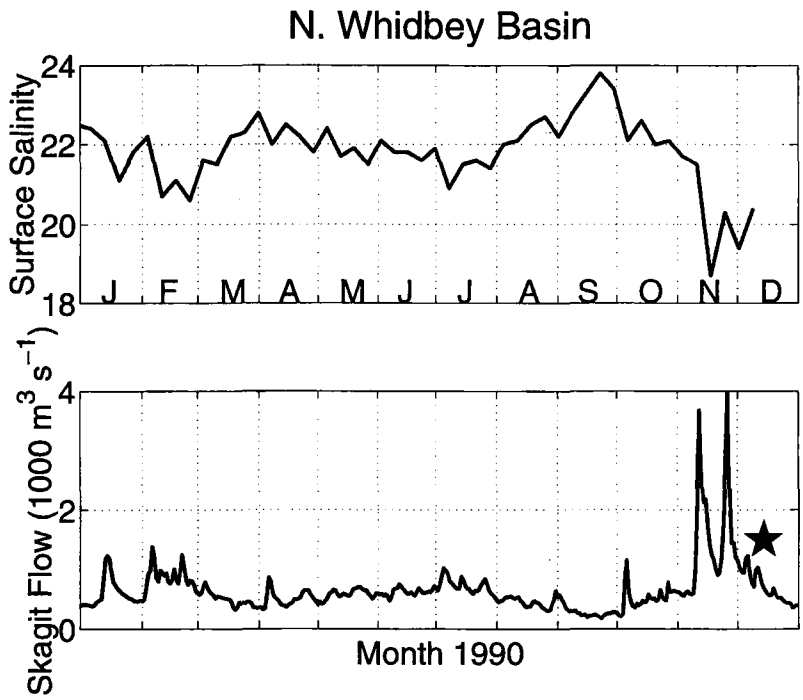

Figure 2. Upper panel: model surface salinity versus time at a point in N. Whidbey Basin (shown by a star in Figure 1). Lower panel: Skagit River volume flow used to force the model (along with seven other rivers). (The river data actually span October 1990 to October 1991.)

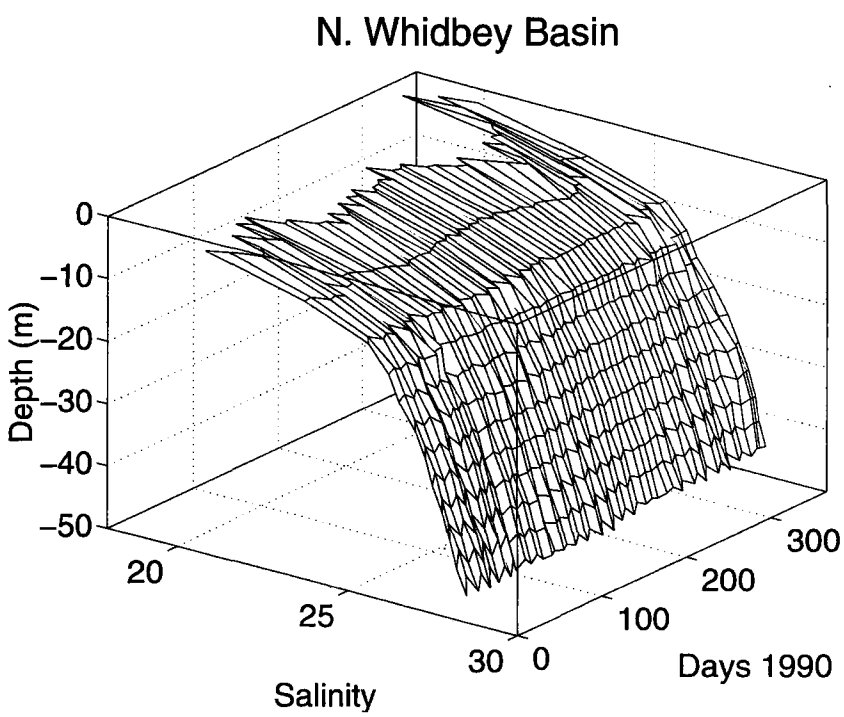

Figure 3. Salinity versus depth and time at the same location in N. Whidbey Basin. The deep salinity changes little; most changes in stratification are due to river-forced changes in surface salinity.

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I am indebted to Laurie Connell, Mike Jacobs, and Vera Trainer for their many patient lessons on algae; however, any gaffes of algal concept or vocabulary are mine alone. Mitsuhiro Kawase provided the numerical results.

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Anatomy of a Bloom: *Heterosigma carterae* in Puget Sound 1997

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University of Washington

Introduction

A massive bloom, of the alga *Heterosigma carterae*, occurred in the main basin of Puget Sound during mid-July 1997. This bloom was responsible for finfish losses in both commercial and research net-pens. Although commercial fish mortalities resulting directly from the alga were low (~4%), total financial losses reached nearly $2.5 million because of towing associated costs. Currently, towing pens to safer waters is the most frequently used method of risk management in Puget Sound. This involves many hours of preparation and remains a costly form of minimizing losses from these potentially toxic blooms. In order to identify factors that may predict bloom conditions, thus giving advance warning, we have instituted a long-term ecological study in a location that has had finfish mortalities resulting from *H. carterae* blooms in the recent past.

Background

H. carterae is a bi-flagellated, unicellular golden-brown microalga, about 10-20μm in diameter. This alga can be somewhat pleomorphic (it can have varied shapes) (Hara and Chihara 1987). Because of its ability to swim, *H. carterae* is very competitive in stratified waters, where it gleans nutrients from below the pycnocline at night and harvests light for photosynthesis in the upper layers during the day (Watanabe et al. 1983).

World-wide distribution of this raphidophytic alga is restricted to euryhaline coastal waters (Honjo 1992) where *H. carterae* has been associated with net-penned fish deaths primarily in the Pacific (Honjo 1992). Its appearance in the northeast Pacific has been reported since Strait of Georgia monitoring began in 1967 (Taylor and Haigh 1991) and the first reported finfish deaths were in tribal owned ponds off Lummi Island in 1976 (Jefferson 1976; Gaines and Taylor 1986). Conditions leading to blooms of *H. carterae* can be predicted in some areas. The Inland Seas of Japan have numerous blooms beginning in early spring and lasting into late fall (Honjo 1992). These events have been closely attributed to eutrophication and high nutrient supply (Honjo 1992). Extensive studies in Narragansett Bay, RI, found bi-annual blooms in May–June and October (Tomas 1980) where water temperature and salinity were critical, but eutrophication was not a factor. Closer to this area, workers in British Columbia have been able to predict blooms in areas affected by the Fraser River plume by monitoring temperature and salinity (Taylor and Haigh 1991). Occurrence of annual *H. carterae* blooms in the Strait of Georgia coincide with a water temperature in excess of 15 _C and salinity of 15 ppt (Taylor and Haigh 1991). Typically *H. carterae* blooms are first observed during the end of May, soon after these environmental conditions are observed, and blooms can last as long as stable water stratification remains, often until September.

Blooms of *H. carterae* in Puget Sound are infrequent, the last large main basin bloom occurred in July 1990, and caused significant salmon mortalities in both commercial and research facilitates (Harrel 1990). Small blooms have been reported near Port Orchard in 1993 (Rensel 1995), one near Case Inlet (south Puget Sound), which caused fish losses in September1994 (Hershberger et al. 1997), and several small sustained blooms along the west side of Bainbridge Island, near Brownsville, WA, and in Liberty Bay (Bernier 1996).

Clam Bay 1995-1997

Less frequent occurrence of *H. carterae* blooms in main basin Puget Sound pose a prediction challenge to growers and researchers alike. To determine which factors can be used as early warning predictors of these blooms in Puget Sound, we instituted a long-term ecological study in Clam Bay,

located within Rich Passage. This site was selected because it has both commercial and research salmon pens that were severely impacted during the 1990 bloom (Harrel 1990), easy access without a boat, and suitable sites for semi-permanent equipment deployment. A set of physical and biotic indicators was monitored on a weekly basis between July 1995 and August 1997 (Table 1).

Table 1. Parameters monitored in Clam Bay, WA July 1995-August 1997.

Incident Light	Water Temperature (datalogger)
Dissolved Organic Carbon (DOC)	Air Temperature
Nitrogen Panel (NO_2; NO_3; NH_4)	Phosphate
Conductivity (converted to salinity ppt)	Dissolved Oxygen
Secchi	Silica
Total Bacteria	Species Composition
Chlorophyll	pH

No *H. carterae* bloom was reported in Clam Bay during 1995 or 1996; however, on 14 July 1997, aerial surveys located several small blooms off of the east side of Bainbridge Island. The water was quickly covered with rusty-brown streaks of *H. carterae* cells. These blooms spread rapidly, carried by currents and tide, until it eventually covered >3000 km^2 (18 July). As rapidly as the bloom spread, it began to disintegrate, aggregations of dead cells were seen floating in the main basin on 21 July and by 29 July only fragments of the bloom remained in shallow embayments. In Clam Bay, the highest cell densities were routinely found at 2-m depth, reaching a maximum of 7.93 million cells L^{-1} on 18 July. Because of the herding and diurnal vertical migration phenomena observed in these blooms (Wada et al. 1985), exact cell numbers are difficult to obtain. Samples taken at the surface, when the bloom was beginning to disintegrate and cells were sticking together in mats, had higher counts (up to 42.48 million cells L^{-1}). The cell morphology of this alga changed throughout the bloom with the typical "potato" shaped cells observed during the early days, progressing to a "potato chip" shape by 22 July and with the first cyst, or non-motile round cells, observed on 23 July.

Net-pen finfish impact varied by species and pen location (Table 2). Most fish mortalities at the NMFS pier in Clam Bay occurred early in the bloom, on or before 17 July. Global Aqua sustained significant losses attributed to towing, rather than directly from *H. carterae* mediated mortalities. Similar mortalities were observed between pens towed from Rich Passage and those which remained in Clam Bay (~4%).

Table 2. Fish mortality by species from net-pens in Clam Bay WA, July 1997.

Owner	Species	% Mortality	Number
NMFS	Chinook	~10	407
NMFS	Coho	100	326
NMFS	Sockeye	<.1	4
Global Aqua	Atlantic	~4	200
Global Aqua*	Atlantic	~4	28,552

* Pens towed from Rich Passage into Colvos Passage and east of Vashon Island, Puget Sound.

Nutrient inputs from the Fraser River have been postulated to be underlying stimulation for extended *H. carterae* blooms in Sechelt inlet (Taylor et al. 1994). To explore nutrients as stimulating factors in *H. carterae* blooms in Puget Sound we sampled on a weekly basis in Clam Bay. The nutrient (nitrogen and phosphate) profile among the seasons was very similar, except after the 1997 *H. carterae* bloom reached Clam Bay (16 July). Nitrate levels dropped to 1.42 μM and slowly rose back to normal summer levels (~14 μM) within 5 days (Figure 1). This decrease in nitrate levels is most likely a consequence of the *H. carterae* bloom and not a factor involved in bloom initiation, thus nutrients were not useful as a predictive indicator.

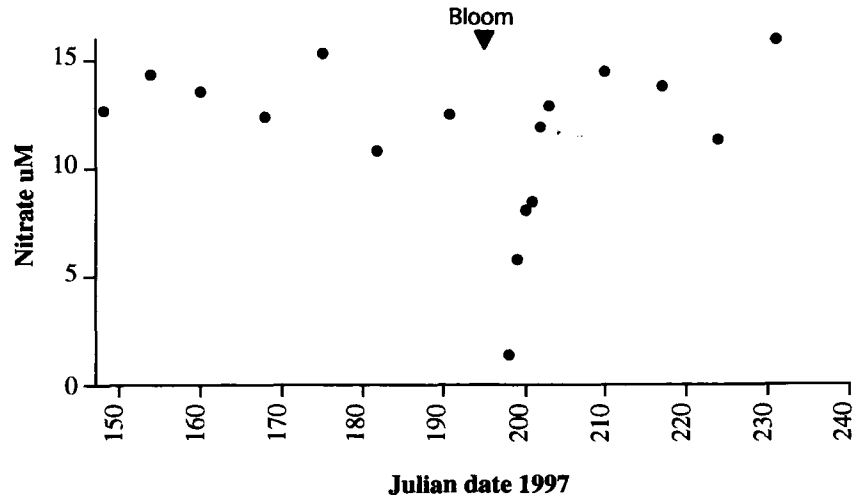

Figure 1. Nitrate levels in Clam Bay, WA from July 1997. The *H. carterae* bloom is indicated by an arrow.

As in areas impacted by Fraser River plume, both temperature and salinity were the parameters that displayed the most striking correlation with this *H. carterae* bloom. Water temperatures at 1 m were significantly higher in 1997 as compared with the previous years (Figure 2). The maximum water temperature recorded during 1995 and 1996 was 13.8 _C. Temperature spikes began in early 1997 gradually rising as the season progressed. These temperature spikes were associated with neap tides and reached a peak of close to 17 _C. This 1997 *H. carterae* bloom did not occur until after the water temperature rose above 16 _C, close the 15 _C target for Fraser River delta monitoring program.

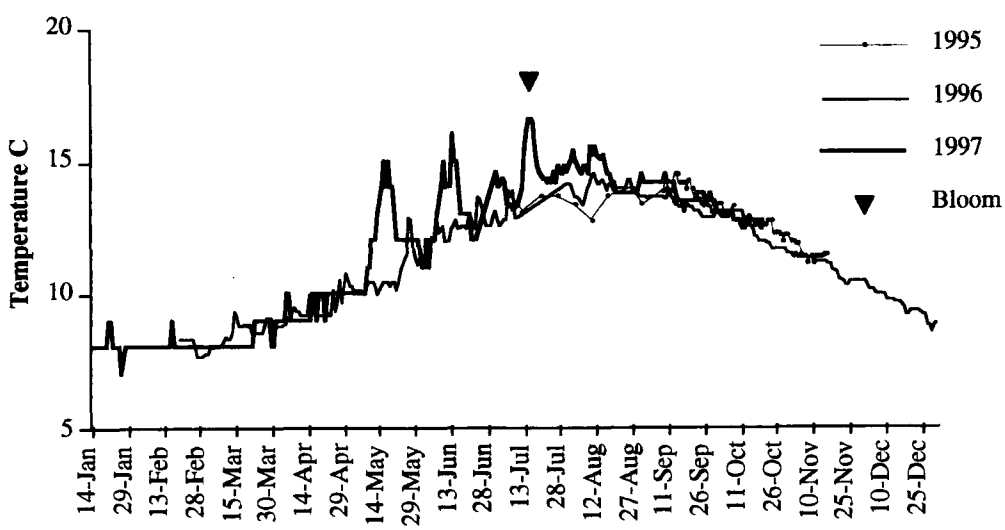

Figure 2. Surface water temperature (1 m) in Clam Bay, WA 1995–1997. Bloom is indicated by an arrow.

Shallow water column stratification (both temperature and salinity) was observed only during the early periods of this bloom and at no other time during the project (Figure 3). Typical surface (1 m) salinity during previous summers was between 21 and 22 ppt. During the 1997 *H. carterae* bloom, salinity (1 m) dropped to 19.4 ppt, and did not approach the 15 ppt target for the Fraser River monitoring program. Although the gradient from surface to bottom was small for both salinity and

temperature, a shallow stratification was able to develop by mid-July during the bloom, and subsequently broke down rapidly by 21 July.

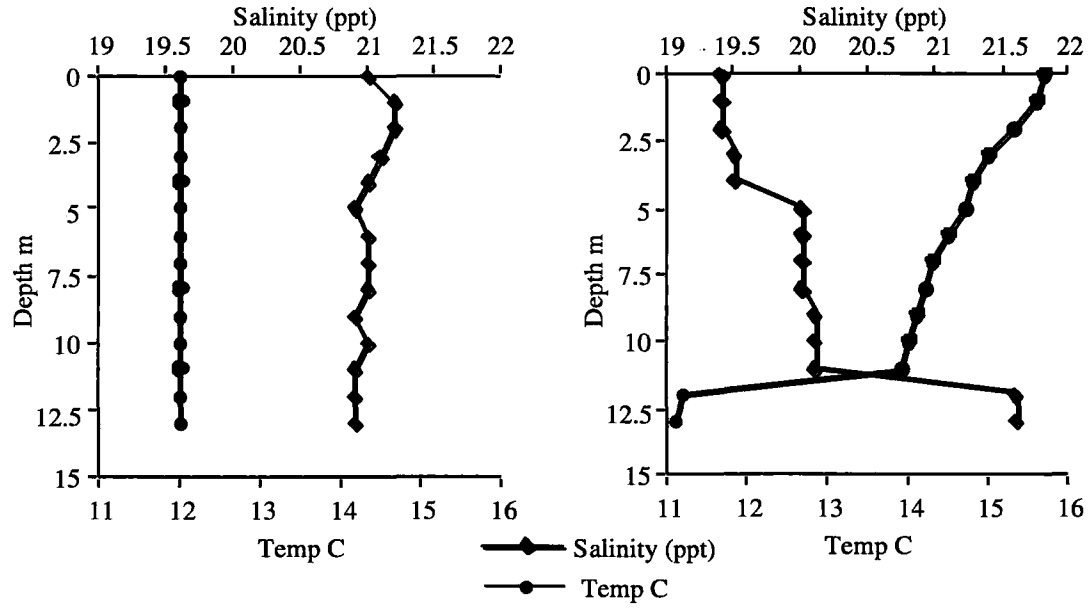

Figure 3. Shallow stratification in Clam Bay, WA. Temperature and salinity profile from (a) typical summer—17 June 1996 and (b) bloom—17 July 1997.

Conclusions

Puget Sound blooms of *H. carterae* occur somewhat later in the season than those in Japan, Fraser River delta and Narragansett Bay (July rather than May). This organism bloomed when the water temperature reached ~16 _C and the salinity dropped to ~19 ppt again, somewhat different from the 15°C/ 15 ppt target for the Fraser River area. The exact temperature and salinity may not be as critical as the development of shallow stratification (5 to11 m). Stratification in Puget Sound is transitory; this 1997 episode was very short-lived, disintegrating within days. We found that the water temperature profile during 1997 was very different from past years. The source of this warmer water has yet to be identified. In summer, the average epilimnion temperature of Puget Sound is somewhat colder than the Fraser River delta, Inland Seas of Japan and Narragansett Bay, and it does not generally maintain stratification during summer months. Therefore, Puget Sound may be less likely to exhibit major *H. carterae* blooms than areas that have warmer water and can maintain stratification. Colvos Passage, on the west side of Vashon Island, has a net northward circulation fed through south Puget Sound during all tidal cycles and remained clear of *H. carterae* during 1997. This makes it an attractive refuge for towed net-pens provided the bloom remains excluded from south Puget Sound.

Although massive, this bloom was not as lethal as the one in 1990. Finfish mortalities in 1997 were light (~ 4%), in comparison with 1990, where many pens experienced 100% mortality (Harrel 1990). The major damage during the 1997 bloom was the loss of fish from research projects and costs attributed to commercial pen towing.

Determining environmental indicators for early warning of potential blooms is an important goal. Increased local rainfall (51% above average) during the month of June 1990 was hypothesized as a contributing factor in the 1990 *H. carterae* bloom (Rensel 1995). Rainfall patterns in May, Jun, and July for 1995–1997 (NOAA regional data center) did not show a pattern correlating with salinity drops at Clam Bay (data not shown). Therefore, it is unlikely that local rainfall had a significant impact on the pycnocline development observed in Clam Bay during July 1997.

Surface water from Admiralty Inlet has been suggested as a potential early warning monitoring tool, because that site was warmer (15 _C) and less salty (19 ppt) than usual 10 days before the 1990 *H. carterae* bloom (Rensel 1995). Dense, cold, saline ocean water flows into Puget Sound at depth and warmer, less salty water exits primarily on the surface (Ebbesmeyer and Barnes 1980). Therefore, monitoring surface water in Admiralty Inlet will give useful information for the early "hind-casting" steps in model generation but will not be an effective bloom early warning indicator. Further research, to determine the environmental factors that produce warmer and stratified surface waters, is critical for understanding bloom initiation events. These data, combined with information accumulated from long term studies sites around Puget Sound, such as this one, may provide suitable starting points for numerical models, leading to determination of early warning parameters.

Acknowledgments

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A *Pseudo-nitzschia* Bloom in Penn Cove, Washington During the Summer 1997

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Introduction

The first documented toxic algal bloom caused by a diatom was in 1987 off the coast of eastern Prince Edward Island, Canada (Bates et al., 1989). The excitatory neurotoxin, domoic acid (DA), produced during this episode resulted in death or acute intoxication of many humans following their ingestion of contaminated blue mussels (Bird et al., 1988; Wright et al., 1989). Since 1991, the Washington Department of Health (WDOH) has been measuring DA seasonally in razor clams collected on the Washington coast, sometimes at levels above the regulatory limit (Horner et al., 1996). The agency has also implemented a routine monitoring program for DA in the inland waters of Puget Sound utilizing existing sentinel mussel stations supplemented by monitoring of commercial shellfish species.

We were alerted in early July 1997 by WDOH officials to elevated levels of DA in commercial mussels provided for monitoring by a shellfish farm located on the eastern side of Whidbey Island. This commercial mussel farm, which supplies mussels year-round to many coastal regions of the U.S., was established in Penn Cove due to the unique hydrographic and geographic features of the embayment that make it the most prolific mussel farming area in the state. The geography of the eastward-facing cove makes it a poorly flushing nutrient trap for the outflow of the Skagit River system. This factor combined with high amounts of sunshine in the area due to the rain-shadow effect of the Olympic Mountains turns Penn Cove into a "bay of plankton soup." The appearance of blooming phytoplankton in the cove at some time during early summer months for the past several years (Ian Jefferds, Penn Cove Mussels, pers. comm.) makes it an ideal location for the study of environmental influences on bloom initiation, concentration and dispersal. Our measurements of physical and biological parameters and their correlations with *Pseudo-nitzschia* species abundance during July and August 1997 at several sites within Penn Cove, Whidbey Island, and in neighboring waters of Saratoga Passage are detailed in this paper.

Materials and Methods

Field Sampling

Sampling at five stations, approximately 50 m offshore (solid circles, see Figure 1) in Penn Cove, Whidbey Island, was at three depths (0, 5, 15 m). Three surface stations (open circles) were also sampled within the cove. Beginning August 5th, surface stations near or outside the mouth of the cove (open circles) were also sampled to measure spreading into Saratoga Passage.

Depth, temperature, and salinity were obtained with a SeaCat SBE19 (Sea-Bird Electronics, Inc., Bellevue, WA) conductivity-temperature-depth profiler. Five-meter and 15-m water samples were collected using 2.5-L Niskin bottles. Surface samples were collected by bucket. Sub-samples from the Niskin bottle were processed as described below for *Pseudo-nitzschia* cell counts. Station locations were determined using a hand-held global positioning system (Magellan 5000D).

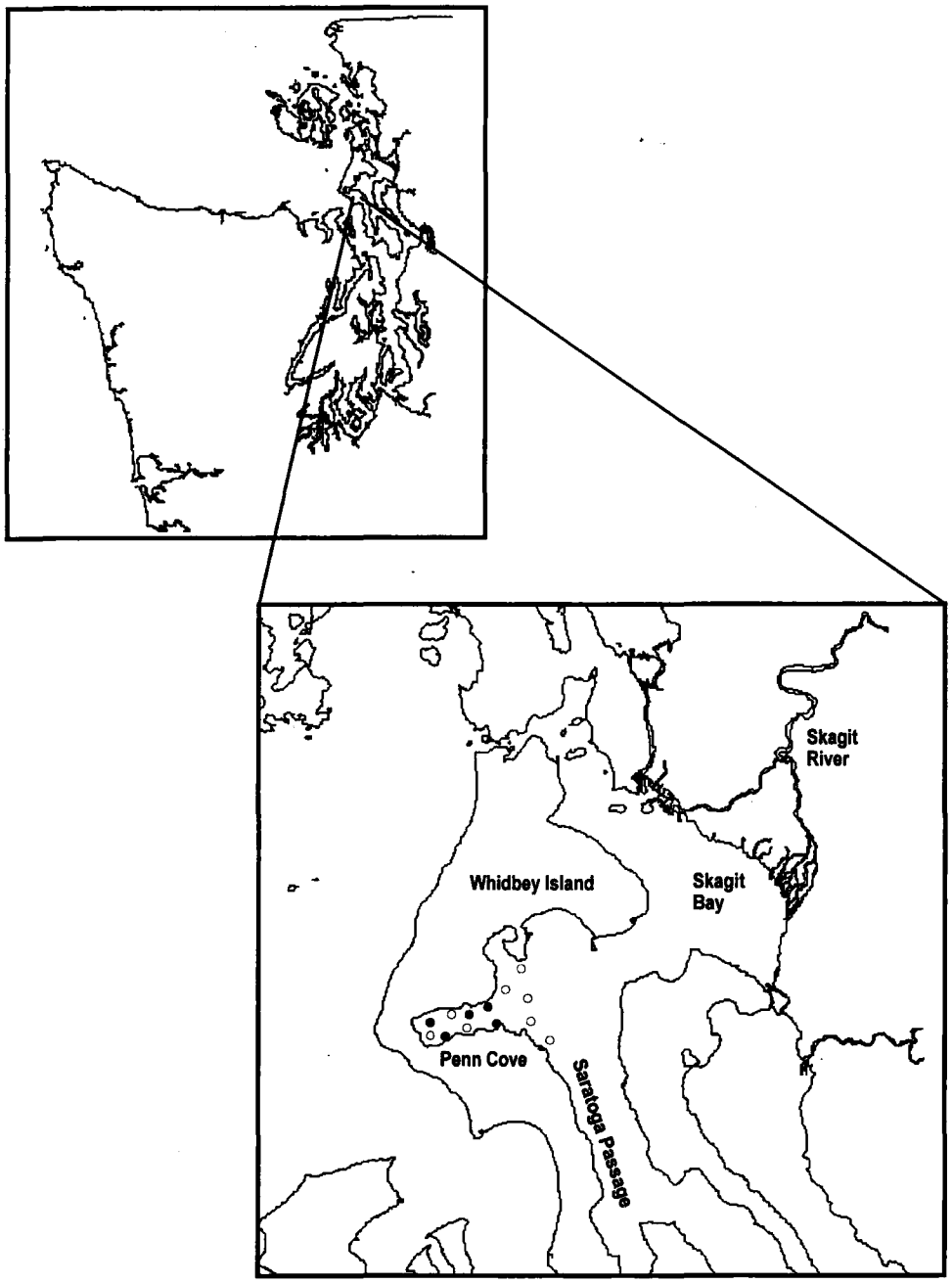

Figure 1. Sampling locations in Penn Cove, Washington.

Laboratory Analyses

Phytoplankton samples were collected using 0.25 m diameter nets having a mesh size of 20 µm. Cells were identified to the genus level and counted using light microscopy. Shellfish toxicity data for mussels collected from Penn Cove was made available by the WDOH.

Results and Discussion

Algal blooms of *Pseudo-nitzschia*, *Chaetoceros*, and *Noctiluca* have been observed in Penn Cove in the early summer over the past few years, several days after a shift of winds to a southeasterly direction (Ian

Jefferds, pers. comm.). In 1997, conditions were favorable again for a phytoplankton bloom in Penn Cove, which was first observed during early July (M. Kirkpatrick, WDOH, pers. comm.). The presence of *Pseudo-nitzschia* species as a dominant component of the bloom was confirmed in a water sample obtained from the cove on July 10th. The levels of DA in mussels harvested from Penn Cove reached a maximum of 3 ppm (μg/g) on July 6th and 10th (Table 1). These high levels were accompanied by winds that shifted from a westerly to a S/SE direction on July 7–10 at a maximum speed of 10 knots on July 8th (Figure 2).

Table 1. Domoic acid levels in Penn Cove mussels.

Sampling Date	Domoic Acid
June 29	< 1 ppm
July 6	3 ppm
July 10	3 ppm
July 13	2 ppm
July 23	< 1 ppm
July 27	NTD

NTD = no toxin detected
ppm = parts per million
Data were provided by WDOH.
Measurements made after July 27th were NTD.

Daily observations of current movement indicated that wind and rainfall were the primary factors that influenced mixing within the cove (Ian Jefferds, pers. comm.). The highest average wind speeds for the three-month period from June–August were measured on July 1st at above 15 knots. Average air temperature (_C) showed a general rising trend during the early part of July in comparison to the latter part of June (Figure 2). Heavy rains experienced in June and the early part of July ended for a several week period beginning on July 10th. Discharge from the Skagit River was above average volumes (USGS Water Information System, historical data), especially during the time from June 17–18 and July 9–12 due to periodic summer warming trends (Figure 2) and uncommonly high levels of snowfall earlier in the year resulting in necessary release of water from upstream dams.

High winds and rains experienced on July 1st may have facilitated mixing of the water column, thereby delivering nutrients from depth to the surface, especially in shallower areas on the western edge of the cove. The increase in surface runoff and winds blowing into the cove from a S/SE direction beginning on July 7th may have subsequently initiated a period of stratification, setting the stage for a sustained algal bloom in the poorly-flushed cove. A period of hot, calm summer weather (average daily air temperatures at 14–16 _C and average daily wind speed of less than 10 knots) after July 10th further stabilized the water column and intensified stratification. On July 28th, the maximum number of *Pseudo-nitzschia* cells were associated with relatively low salinity water of 24–25 ppt, which was above highly stratified waters. On this date, high numbers of *Pseudo-nitzschia* cells, up to 13 million cells/L, were observed above the thermocline at 2 m. The buoyant plume of low salinity water at the mouth of the cove, likely resulting from the massive volume of Skagit River runoff on July 9–12, appeared to direct the position of cells, moving them into the shallower waters toward the western end of the cove. Previous association of an isolated patch of toxic algae with low salinity water has been documented in a bloom of the dinoflagellate *Alexandrium* off the southwest Gulf of Maine (Franks and Anderson, 1992; Franks, 1990). This buoyancy front was formed by the upper bending of the halocline at the mouth of the cove, which separates the lighter surface water from the dense deep water. The warm, fresher water formed a thin lens on the upper 2–3 m throughout the cove, even near the western edge as evidenced in the vertical profile plot. Similar vertical profiles were observed at all stations throughout the cove on July 28th. In summary, factors contributing to strong stratification of the water column on this date included a neap tide on July 26th, sunshine, and freshwater input into the cove.

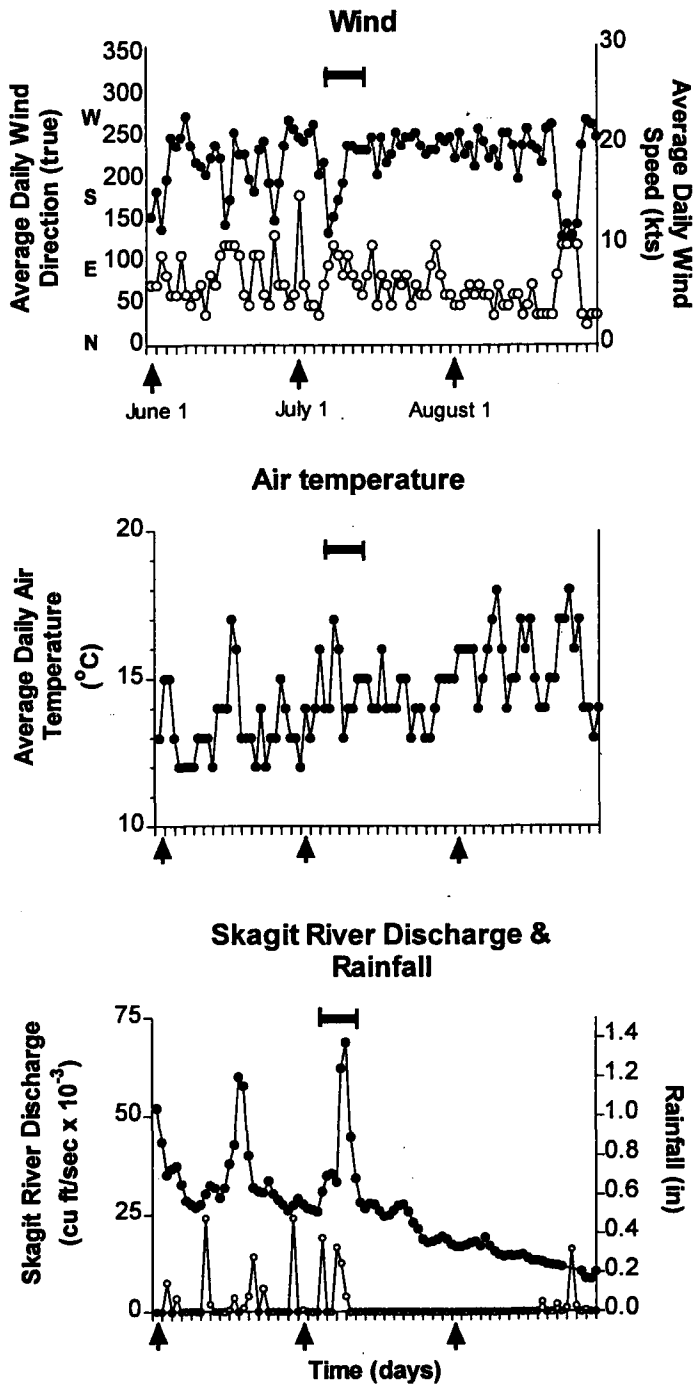

Figure. 2. Environmental data during June, July, and August 1997 at locations near Penn Cove, Washington. Skagit River discharge data (closed circles) is measured at Mount Vernon, a United States Geological Survey Water Information Station about 30 km northeast of Penn Cove, and approximately 11 km from the point of discharge into Skagit Bay. Wind direction (solid circles) and speed (open circles), air temperature, and rainfall data (open circles) are obtained from the Whidbey Island Naval Air Station National Climatic Data Center (NOAA), which is located about 10 km north of Penn Cove. Daily averages were computed from hourly measurements during a 24-hour period. Bars above each graph indicate the period of maximum DA levels in Penn Cove mussels.

On August 5th, the vertical profile changed dramatically. Stratification decreased substantially causing relaxation of the buoyancy front. As a result, a large proportion of the total *Pseudo-nitzschia* were mixed to all depths at the mouth of the cove. In contrast, on the west side, all measurable *Pseudo-nitzschia* were in surface waters above the thermocline at approximately 2 m. Maximum cell number, which decreased about five-fold from July 28th to approximately 3 million *Pseudo-nitzschia* cells/L on August 5th, were found at the western edge and also at the mouth of the cove.

One week later, on August 12th, cell numbers of *Pseudo-nitzschia* increased to a maximum of 4 million cells/L, as a dense patch of cells became entrained below the halocline to reach a maximum at 5 m. This entrainment appeared to be directed by a buoyant plume of low salinity surface water. In comparison to the previous week, surface water warming and increased stratification were observed on this date. Contributing to this stratification were low average wind speed, relatively high average daily air temperatures, and a neap tide on August 11th.

On August 21st, the inner locations of the cove were completely mixed, with a small freshwater lens observed at the mouth again due to exchange with fresher waters of Saratoga Passage. Rain on August 20th, winds shifting periodically to a southerly direction during the two weeks prior to this date, and a spring tide on August 18th facilitated the mixing of the cove. Total *Pseudo-nitzschia* dropped to a maximum of 700,000 cells/L, located at the center of the cove as a surface patch. Most cells were unhealthy (noted as thinning and colorless or fading chloroplasts) especially a localized band of cells that were measured at the western edge of the cove at 15 m depth. Gentle mixing of the cove during mid-August and small fluctuations of tides may have caused some of the cells the were at 5 m depth on August 12th to be entrained to 15 m on August 21st.

A movement of *Pseudo-nitzschia* from nutrient-poor surface waters into the higher-nutrient mixed layer was observed over the period of sampling from July to August. This may be a strategy that allows basal metabolism of *Pseudo-nitzschia* cells to occur at depth, where temperature and light intensities are low. These factors may enable enough *Pseudo-nitzschia* to survive at depth for several months until conditions for bloom formation are ideal.

Conclusions

In June and July 1997, massive volumes of Skagit runoff due to abundant snow melt facilitated the flow of lowland drainage, bringing nutrient-rich fresh waters to neighboring embayments, including Penn Cove. The combination of nutrient-rich runoff, rain, and high south to southeasterly winds in early July followed by lighter winds, sunshine, and a neap tide resulted in prime conditions that allowed *Pseudo-nitzschia* species several days of uninterrupted growth to build their standing stock to bloom proportions. A buoyant lens of fresh water strongly influenced the position of the bloom, especially during neap tides on July 28th and August 12th when mixing within the cove was minimal. Less stratification was evident on sampling dates closer to spring tides (August 5th and August 21st), especially toward the western (inside) edge of the cove, possibly due to advection of less-stratified water from Saratoga Passage. This advection of cells within a buoyant plume, common to algal blooms in shallow seas (Franks, 1992), resulted in entrainment of isolated patch of unhealthy cells to a depth of 15 m on August 21st.

This study of the concentration and dispersal of a *Pseudo-nitzschia* bloom in Penn Cove provides some predictive elements of toxic bloom occurrence in embayments within Puget Sound. Elements of this model include factors that contribute to initiation, concentration, and dispersal of the *Pseudo-nitzschia* bloom. These factors include:

Initiation

- high runoff from the Skagit River,
- high winds and rain, and
- increased air temperature;

Concentration

- dramatic shift of winds to a southeasterly direction,
- subsequent sustained light winds,
- sunshine, and
- neap tides or reduced mixing;

Dispersal

1. possible depleted nutrients, and
2. exchange of Penn Cove water with Saratoga Passage water, predominantly during spring tides.

Long-term observation of *Pseudo-nitzschia* bloom phenomena in Penn Cove and other Puget Sound locations will further document the mechanism of bloom initiation and dispersal in this unique system of saltwater embayments.

Acknowledgements

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7B: Harmful Algae in Puget Sound: From Research to Management

Questions & Answers

A: [In response to a question that was not recorded:] OK, what you're thinking about is a publication put out by the Washington Sea Grant Program called "Gathering Safe Shellfish in Washington." At least, I think that's it. This does not have the different languages, as far as I know. But you could ask the person at the Sea Grant desk out here.

Comment: The other place to start is the State Department of Health.

Cox: Our department has a number of small publications and we have a few big single sheet posters that have different languages printed on it. There are about seven or eight languages, but it doesn't sound like what you're describing as a three part poster. Ours is just one part.

Q: [Unrecorded question about the temperature regime.] Was it unusually warm?

Cox: Out off the coast of Long Beach, water temperatures were recorded at 17 degrees centigrade. At 20 degrees centigrade, oysters spawn, and normally this time of year (I'm not an expert on the oceanography out there) I believe the temperatures are closer to 10 or 11 or 12 degrees. So very definitely we had elevated temperatures. There weren't people out taking water samples all over throughout these areas, but we generally had a calm, sunny condition and I think it probably created a warm stratified layer on the surface. Again, I'm not an oceanographer and I can't say that we documented that, but I suspect that that may have played a part in the blooms.

Q: Department of Ecology has records of temperatures in Willapa and Gig Harbor and Puget Sound areas, of course. We also have a special project in Willapa Bay and we have moorings there and we are continually monitoring temperature every 15 minutes in addition to additional study that started in the end of July. There's a poster at this conference displaying that temperature data.

Cox: When the shellfish samples inside Willapa Harbor went from nothing to "over the limit" from the 10th to the 13th, I think that really demonstrates that the changes occur very abruptly, and that in order to document those changes and the conditions that cause the event itself, you almost have to be doing daily sampling and testing because, if you go out twice a week or once a month, you easily could miss a bloom like this.

Q: But if you have every 15 minute sampling, then that gives some potential predictive value that when you have these unusually high temperatures, step up the monitoring.

Cox: It could do that, yes.

Q: [Unrecorded question] about how long do these animals retain PSPs?

Trainer: No. That was one thing I did want to look at, but I had so many things that I wanted to look at, I had to narrow it down. But somebody in Alaska is doing a study with Jack Wekell.

Q: Is that a probable explanation for why you see it and you don't see it in the mussels?

A: That could be. I don't know. This is the first study of any kind that's been done like this. It could just be variability alone.

A: [In response to an unrecorded question:] Like next month. I mean that sort of data already exists because it comes out of the weather prediction models that used it in atmospheric science. We're working to incorporate it right now. That's not a fundamentally hard problem. The physics already exists in the model, it just wasn't done on the first year long run.

Trainer: [In response to an unrecorded question:] That's an excellent question and I'm trying to track that data down. It turns out that as far as aerial photographs, nobody was taking pictures then from any of the sources that I had tried to look for and I'm looking into some satellite images now. I'm not sure they're going to have the resolution that's quite high enough for me for the beginning of the bloom to see where the bloom began.

Trainer: [In response to an unrecorded question:] That's a good question. Late in August, we found a large number of cells that had actually sunk to the bottom of the cove or to 15 meter depths. They were somewhat unhealthy-looking cells, but they were alive, and my theory is that these cells are able to live at depth in cooler temperatures and in maybe a different life stage, an asexual vs. sexual life form, to live at depth until the conditions become prime for a bloom in the next year. But that's just a theory at this point. I think they're resident within the cove. OK, now I'd like to open the floor to discussion, to any of the questions for any of the speakers who spoke during this session. We have a few minutes.

Q: Rita, I'm going to apologize because if you mentioned this, I wasn't here for your talk, unfortunately. Everyone knows about the 800 number the Department of Health maintains when you want to ask or hear a recording whether there are known blooms of toxic or potentially toxic algae, but I wondered if the hotline that you and Jim Postel have, if that is still continuing, and if people generally know about it. You know, if you're out in the Sound and you see a bloom, that you can call this number. Is that still available?

Horner: That number is no longer still available as a separate number, but you can call either my phone number at the University or Jim's and leave voice mail if you do see blooms, and I will be more than happy to give you those numbers. Mine is 206/543-8599 and Jim's is 543-6141.

Q: I'm curious about the effects of grazing... [end of question not recorded]?

A: It appears that some of these organisms are not grazed on by zooplankton. *Heterosigma* is one of those. In fact, it looks like things like ciliates will actually reverse the direction of their aboral cilia I order to get rid of *Heterosigma*. But we do have a little bit of limited data that show that copepods, for example, will graze on *Psuedo-nitzschia* and there are a number of things that will also do some grazing on *Alexandrium*. But whether these will actually control blooms or not, we don't know.

Comment: I just want to add to that. I know there's a funded study on the East Coast looking at viral vectors as a means of mitigation and control of harmful algal blooms. I think we need to be careful with mitigation procedures. That's my feeling.

Q: Yesterday there was presentation on exotic species and they pointed out that San Francisco Bay apparently has been colonized by organisms that filter higher water volumes. Is there any work going on and do any of the panel members know are harmful algal blooms reduced in sites like San Francisco Bay?

A: The fellow at lunch yesterday did say that it definitely decreased the amount of algae in those places. It was a big effect.

Q: Just a follow up to the first question to Rita. Could you give any more enlightenment as to life cycles in some of these organisms?

Horner: How long do you want to stay? The *Alexandrium* life cycle is pretty well worked out and it produces two kinds of cysts. One kind is a temporary cyst that form as the result of poor environmental conditions. These are temporary and only last for a short period of time. The other kind is a cyst that's produced as a result of sexual reproduction and these are so called dormant cysts, the ones that go to the bottom and may sit for some period of time. They actually need a dormancy period before they'll regerminate. For *Psuedo-nitzschia* there is one record, one time from a species from the Antarctic that went sexual for some reason that nobody was ever able to figure out. But there are some suggestions that maybe it also has a sexual life cycle. *Heterosigma* I think just divides but also can form resting cysts. So the life cycles are quite varied.

Trainer: [In response to an unrecorded question:] If you are referring to the study in Penn Cove, I think that those cells were probably directed toward the inner part of the cove by a fresh water lens, so there was a gradient of salinity on the outside and the inside of the cove that, I believe, directed those cells toward the inside because there was a relaxation of that at the next sampling time. Do you want to direct that question to someone else?

Comment: Vera, let me say something about the outside coast that I didn't mention in my talk. Normally, when we're monitoring razor clam on the outside coast, and we're monitoring the shellfish in Grays Harbor and Willapa, we see that the razor clam will show evidence of PSP first. In this bloom that we had in the fall of 1997, that wasn't the case. The razor clams off of Grayland never did show any toxicity whereas the blooms appeared to have originated inside Willapa and Grays Harbor, which is contrary to what we normally think – that the PSP blooms usually move in from deeper water and occur on the outside coasts first. So it's very different depending on where you are.

Q: As someone involved in the shellfish industry and also somebody who enjoyed the sunshine last November, I can't help but wonder about the relationship between the lovely November weather that we had and the fact that we also had the PSP blooms. I guess my question is to Parker. Is there any way to incorporate levels of light? Is there a model?

MacCready: Yes, absolutely. I think that that's part of how the heat budget works and that is something that comes out of the weather data that would be provided by essentially the same people who predict the weather that you hear on the news, are able to provide that kind of information. Especially hindcasted, you know, after the fact.

Q: Going back and reexamining what happened last fall?

MacCready: Oh yes, that would be a lot easier to do than to predict what is going to happen next fall.

Comment: I know that there are skeptics as to whether or not models can be created to be predictive in the case of harmful algal blooms, but I think that we do see some common threads just between the bloom that was observed, the *Heterosigma* bloom off Bainbridge and then the bloom of *Pseudo-nitzschia*, although it was not at high levels in mussels. I think that we have some common factors which do promote initiation and concentration of these blooms. So I'm very excited about the possibility of modeling these efforts.

Mearns: I'm not an expert on this subject, but I've been trying myself to get some remote sensing, some satellite images in California and have gotten frustrated with the resolution and so on. I think I detected a little bit of that in your comment earlier. I'm wondering about the status, it seems to me we do have a big picture thing here that we need to watch and look for and are we being limited by the resources that we have to look at some of these big picture as well as the small scale things like the question that Ron just asked about, do these things really start in the center somewhere. What is our experience with remote sensing, and where do you think it out to be?

A: With regard to ocean colors, we had a satellite sensor up from 1978 to 1986, that was the coastal zone scanner. That died and then in, I think it was a year ago, the Japanese launched a satellite. That had a one-kilometer resolution of ocean colors. That died after about nine months. The US launched a satellite last August, and that's been operational since September. At University of Washington, as part of PRISM, we are now starting to get one-kilometer data and we have to look into all the legal technicalities of posting it on the website, because it is a NASA-industry cooperation. But it has one-kilometer resolution, so that's going to hit the strait and the main basin. The thing that's really exciting for the future, is the year 2000 or 2001: the navy at NRL, in cooperation with industry, will be launching a sensor that has a 30 meter resolution. We're able to start looking at the scale that's really going to be important in terms of Puget Sound. And I'm involved with some of those programs through the office of medical research. So perhaps at about the two-year timetable, we'll be able to come back to this time and see a little bit of information.

Panelist Question: But those are blooms in general, not necessarily harmful blooms. Is that right?

A: It's everything that's the same color as well. But what's interesting and what I didn't realize from some of the comments of the speakers this afternoon, is that is the observations were made by eye, so I think that has some potential. If you know that there's a color development then you can go out and monitor it, then you can get a big picture view to predict with the model.

Panelist: *Heterosigma* would be the one that you could probably monitor using satellite, but some of these others would probably be very difficult because often they are present at very low cell numbers and the blooms may be subsurface. They would be a lot harder to do anything with that way.

Q: Kelly, you mentioned the receptor binder assay, or something like that. Can you jut say a little bit about that?

Curtis: Well, I haven't actually started the work yet and I haven't actually seen the method before. I will be doing the work with Vera, and she knows a lot more about that than I do.

Trainer: Basically it utilizes a purified nerve receptor and a radioactively labeled saxitoxin molecule, and it looks in the sample at the displacement of that radio labeled molecule from the receptor. It's a lab-based biochemical method. It's not used in the field yet, but it's advantages are that many samples can be run on one day and it doesn't use mice or live animals. So we're interested in comparing mouse bioassay data with the receptor binding assay to see about possibly utilizing it for regular monitoring in the future.

Q: What are the relative costs of that?

Curtis: From what I've read, the receptor binding assay costs about 11 or 12 cents a test, excluding labor costs. And the mouse bioassay costs about $11 per test.

PUGET SOUND RESEARCH '98

SESSION 7C

BIRDS AND MARINE MAMMALS

Session Chair:

Mary Mahaffy
U.S. Fish and Wildlife Service

Status and Trends for Selected Diving Duck Species Examined by the Marine Bird Component, Puget Sound Ambient Monitoring Program (PSAMP), Washington Department of Fish and Wildlife

David R. Nysewander and Joseph R. Evenson
Washington Department of Fish and Wildlife

Introduction

The Wildlife Management Program of the Washington Department of Fish and Wildlife (WDFW) was given responsibility in 1991 to design and implement monitoring plans for marine birds, waterfowl, and marine mammals under the Puget Sound Ambient Monitoring Program (Monitoring Management Committee 1988). The bird and mammal portions of the Puget Sound Ambient Monitoring Program (PSAMP) were not funded until the 1991–93 biennium. Study design for the bird portion of the task, along with consolidation of historical databases, was contracted November 20, 1991 to Ecological Consulting Inc. (ECI). Some of the present project staff began in mid-May 1992 under the Game Division of the Wildlife Management Program to direct, conduct, and coordinate this task. The final implementation plan was produced in March 1993 (Nysewander et al. 1993), even though surveys and contract field work were begun during the summer of 1992 and the winter of 1992–93.

Objectives

The Monitoring Management Committee set down the following goals for monitoring of bird resources under PSAMP in 1988:

- To monitor the abundance of selected avian species to identify any significant changes or trends that may be related to pollution, habitat loss, or disturbance; and
- To monitor reproductive success and contaminant levels in birds.

The first goal was addressed by WDFW and resulted in the development of objectives to document through aerial surveys the habitat use, densities, and trends seen over time throughout all of greater Puget Sound for selected key species for two annual periods: summer and winter. Certain species were selected for emphasis in monitoring by the project's implementation plan (Nysewander et al. 1993) using criteria related to usage of or dependence upon marine waters of Puget Sound, to peaks of abundance during our survey windows, and to other concerns due to limited numbers or special vulnerability to humanly caused mortality.

Methods

The surveys primarily utilized a Dehaviland Beaver float plane. The plane flew at 80–90 knots (kt) at an altitude of approximately 65 meters (m) above sea level. The use of an on-board computer linked to a global positioning unit (GPS) provided a record of time and position every 5 to 10 seconds during the survey. Two observers recorded all birds seen along a 50 m wide strip on each side, along with observation times to the nearest 5 seconds. A third person ran the computer, monitored the GPS unit and output, and directed the pilot to different census routes. This track line was then interpolated by computer with the sightings, using the time of the sightings relative to the time and position fixes generated by the GPS. The sampling protocols and methodology, described in greater detail in the marine bird and mammal implementation plan (Nysewander et al. 1993), follow the general methods developed over the last two decades in California and the Pacific Northwest (Briggs et al. 1981, 1987, 1991).

The aerial surveys were stratified by effort into two levels: higher densities found near shorelines and lower densities found offshore or in open waters. Almost all of the nearshore habitat (<ca. 20 m or 10 fa) was sampled by transects that followed the shoreline in a roughly parallel pattern whereas the offshore habitat (>ca. 20 m) was sampled in a zigzag pattern. A turning angle of 90 degrees was initially used on the zigzag pattern. To reduce variance on estimates of bird concentrations found in certain deeper waters, sharper turn angles were subsequently used after the first year, thereby increasing the percentage of offshore area sampled. The flights were extended after the first year to include the Washington state side of the western half of the Strait of Juan de Fuca. After the first year, the nearshore habitat was surveyed in two different ways: 1) the parallel fashion described above for nearshore habitat that was relatively narrow; and 2) a more intensive zigzag or S pattern where the nearshore habitat stretched extensively offshore such as at a river mouth or estuary.

The PSAMP aerial surveys recorded all bird species seen from the high tide line down, but data analyses for monitoring purposes have concentrated on the following set of species: pigeon guillemot (*Cepphus columba*), common murre (*Uria aalge*), rhinoceros auklet (*Cerorhinca monocerata*), marbled murrelet (*Brachyramphus marmoratus*), western grebe (*Aechmophorus occidentalis*), bufflehead (*Bucephala albeola*), two species of goldeneye (*Bucephala islandica and B. clangula*), three species of scoters (*Melanitta perspicillata, M. fusca, and M. nigra*), greater and lesser scaup (*Aythya marila and A. affinis*), and harlequin duck (*Histrionicus histrionicus*). This paper will focus primarily on most of the diving duck species just listed.

The survey data has been incorporated into both computer databases and GIS mapping programs in both the PC and Unix formats. This data is available through standard map products for all species by counts, densities, distribution and habitat use, or indices of population estimates with associated confidence limits. A synthesized historical database of comparable data from studies as far back as 1978 was created through contract. Comparisons of our present work with this historical database has allowed status and trends to begin being evaluated, especially for selected marine species that are restricted to marine waters. Indices of abundance and distribution have been most useful in the summer for diving birds associated with gill net mortality studies and in winter for diving ducks in long-term waterfowl inventories.

Results for Diving Bird Species

Abundance, Distribution, Habitat Use, and Densities

Puget Sound contains more than 3,200 kilometers (km) of marine shoreline. The PSAMP aerial surveys flew between 3,070 and 3,432 km of transects along nearshore habitat and between 1,846 and 3,458 km of transects through the offshore habitat during each summer or winter aerial survey period (Figure 1). The actual proportion of each total habitat area in inner marine waters of Washington sampled ranged per each survey period from 13% to 15% for the nearshore and 3% to 5% for the offshore habitat component.

The winter pattern of overall bird distribution observed by PSAMP surveys differed, both in numbers as well as geographically, from that of summer. These changes included the following:

- A three-fold increase in bird numbers from (63,187–105,094) in summer to (131,674–273,712) in winter.
- A larger number of birds used the southern Puget Sound during winter than summer.
- During winter, waterfowl usage increased along shorelines and river deltas, with certain estuaries, including the Skagit River delta and Padilla Bay, containing large numbers of waterfowl and geese.
- During winter, grebes and loons migrated into the Sound and used protected waters (deeper waters with relatively low currents) in all of greater Puget Sound excluding the Strait of Juan De

Fuca, and portions of the San Juan Islands.

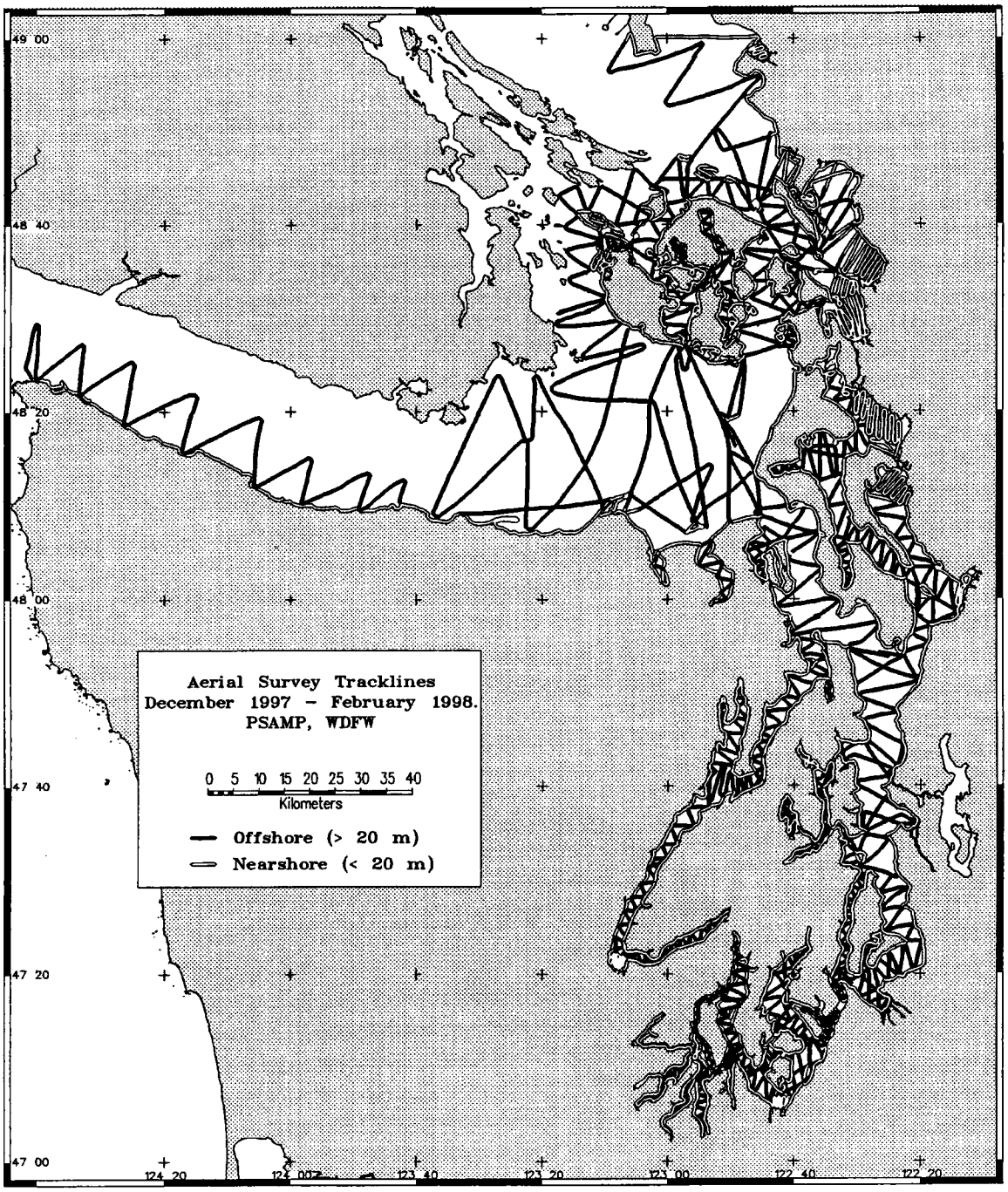


Figure 1. Representative coverage as illustrated by 1997–98 winter aerial survey track lines.

Waterfowl comprised 61–67% of all birds counted during 1994–98 winter surveys ($\bar{x}$ =64.21, s.d.=4.65). Sea and bay ducks comprised 26–41% of the waterfowl ($\bar{x}$ =34.0, s.d.=4.72) depending upon the influx of dabbling duck species into the marine habitat. The diving duck numbers were more consistent from year to year since they did not have the flexibility of utilizing other habitats not surveyed by PSAMP that dabbling duck species could.

Actual on-transect counts of diving ducks ranged from 52,794 to 98,411 in 1994–98, with scoter, bufflehead, and goldeneye species being the most numerous. Scoters made up 33–41% ($\bar{x}$ =36.65, s.d.=2.6), bufflehead comprised 23–24% ($\bar{x}$ =23.08, s.d.=0.63), goldeneyes comprised 15–18% ($\bar{x}$ =16.54, s.d.=0.93), and scaup comprised 6–10% ($\bar{x}$ =7.3, s.d.=2.06) of the diving ducks counted in the 1994–98 winter periods (Figures 2 and 3).

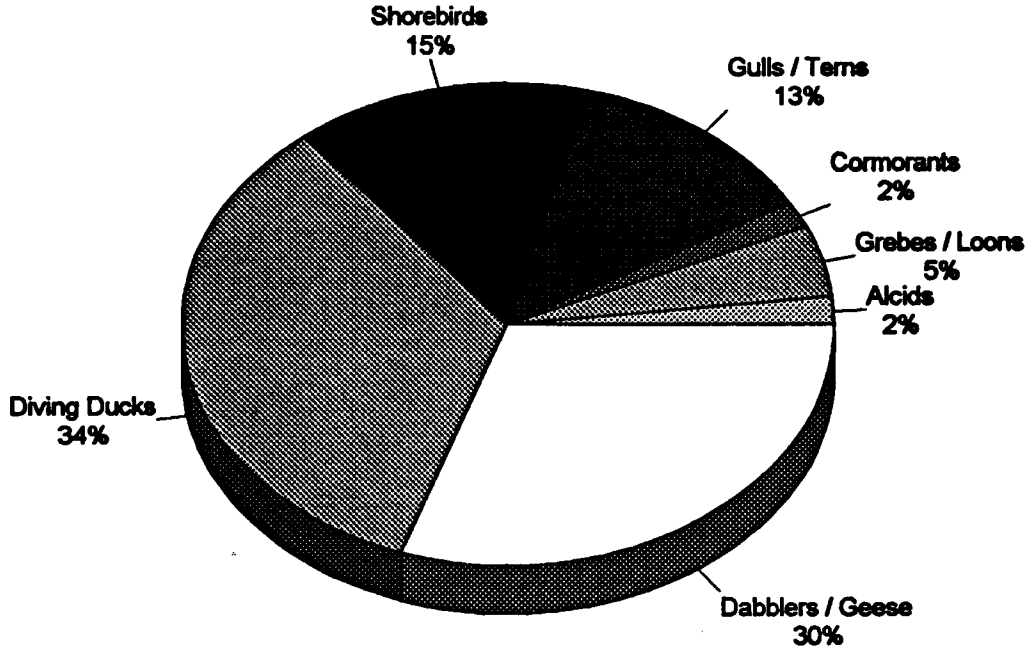


Figure 2. Composition of marine bird populations in greater Puget Sound from PSAMP winter aerial surveys, 1994–98.

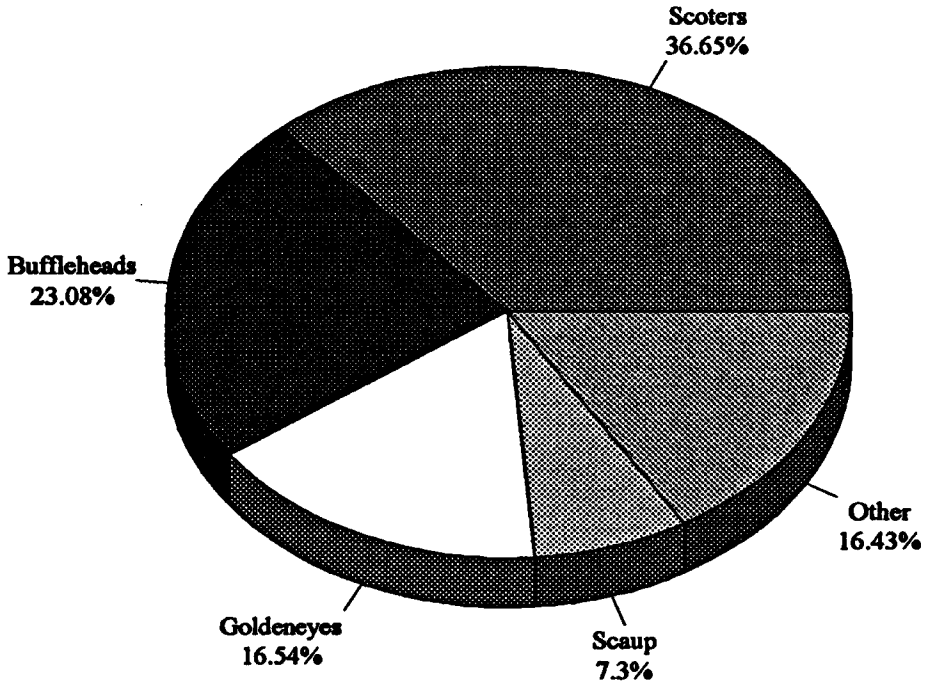


Figure 3. Species composition of sea and bay ducks in greater Puget Sound from PSAMP winter aerial surveys, 1994–98.

Of all the scoters counted on-transect from 1993–98 winter periods, 33–54% were identified to species. Of these, surf scoters comprised 55–80% ($\bar{x}$ =41.22, s.d.=6.91), white-winged scoters comprised 18–40% ($\bar{x}$ =28.29, s.d.=9.17), and black scoters made up 3–9% ($\bar{x}$ =4.67, s.d.=2.06). Nearly all of the scaup counted in PSAMP winter surveys are likely to be greater scaup. Scoter and scaup distribution for Puget Sound recorded in the 1993–98 winter surveys are displayed by densities that result from the counts when combined with survey effort (Figures 4 and 5).

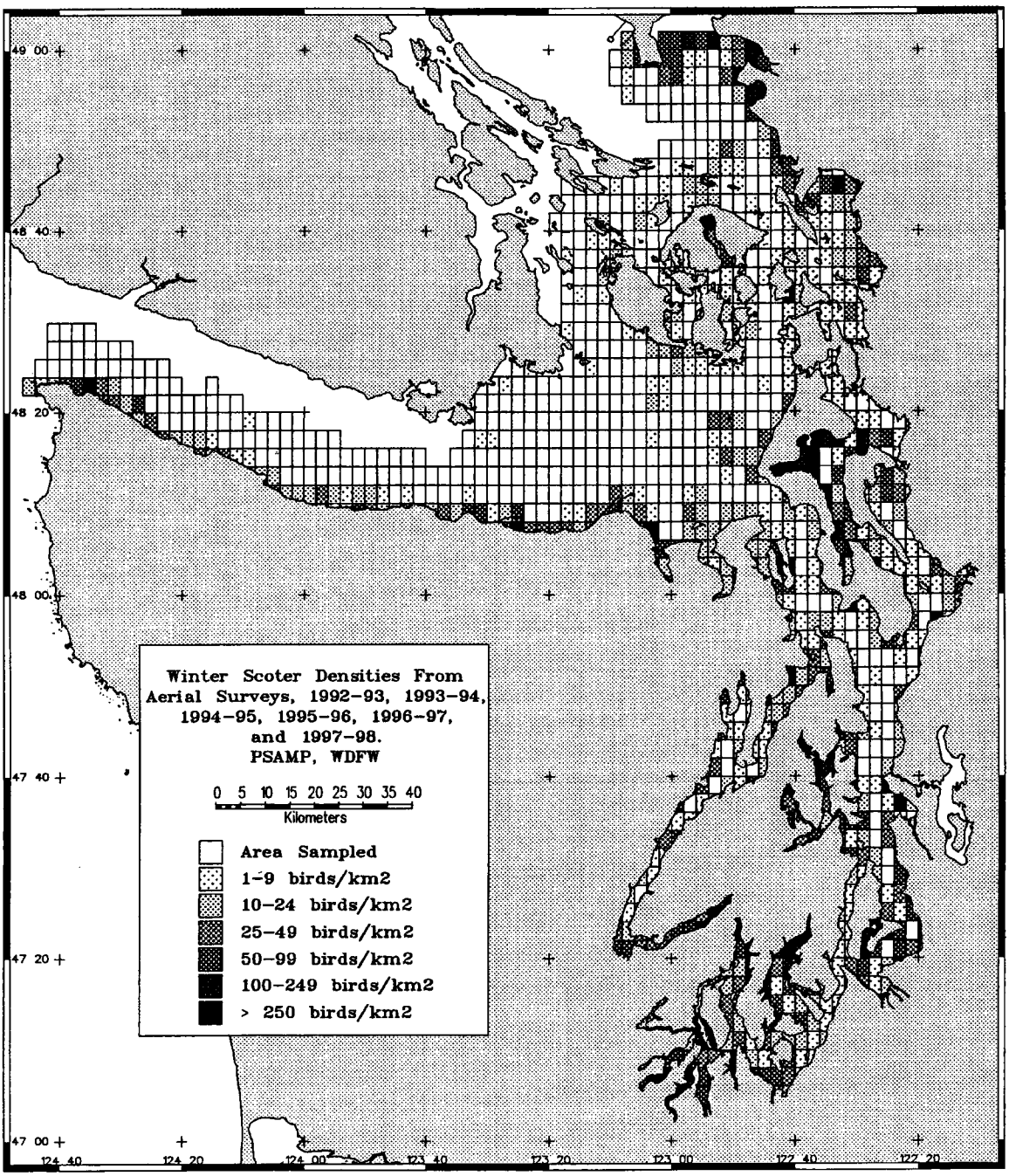


Figure 4. Scoter densities observed winters 1993–98 on PSAMP aerial surveys.

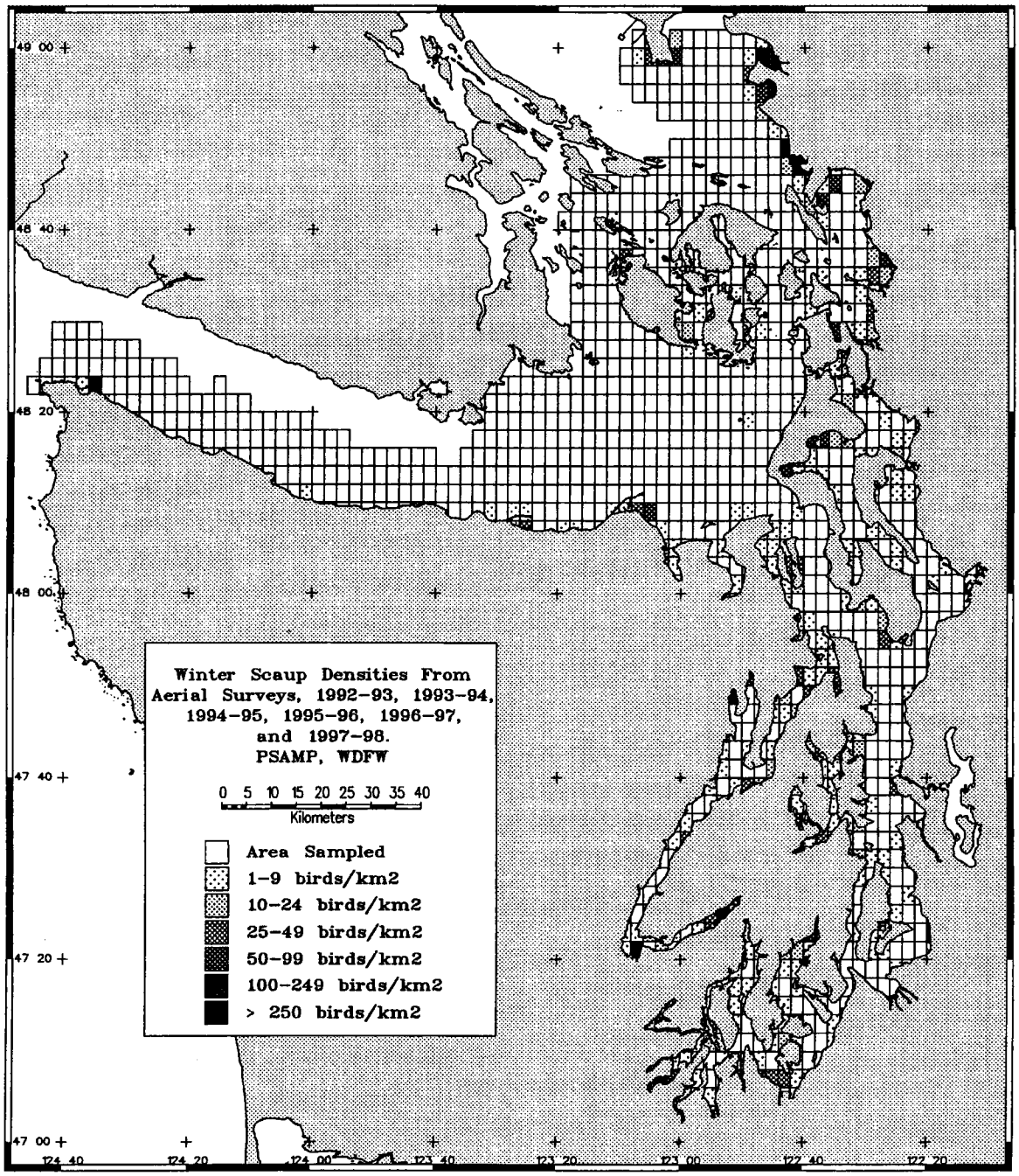


Figure 5. Scaup densities observed winters 1993–98 on PSAMP aerial surveys.

Trends Throughout the Pacific Flyway

Recent reports on status of sea and diving ducks have suggested that certain species have declined (Goudie et al. 1994; Henny et al. 1995; Trost 1998) in certain portions of the Pacific Flyway. We examined what data is available for other portions of the Pacific flyway for the following four diving duck species and compared this with the data now available for greater Puget Sound.

Greater Puget Sound

Comparisons of indices derived from the recent PSAMP surveys and the 1978–79 MESA studies (Wahl et al. 1981) support other Pacific flyway data that suggest wintering scoters and scaup have declined in numbers over the last 15 to 30 years in western Washington and throughout the flyway (Figures 6 and 7). Goldeneyes and buffleheads, using a similar nearshore habitat, do not show this same pattern in marine waters of western Washington (Figure 8). The decline of scaup is probably associated in part with a different wintering pattern on the west coast than that associated with the scoter species; this will be discussed in more detail in the section of this report centering on wintering scoters and scaup in San Francisco Bay.

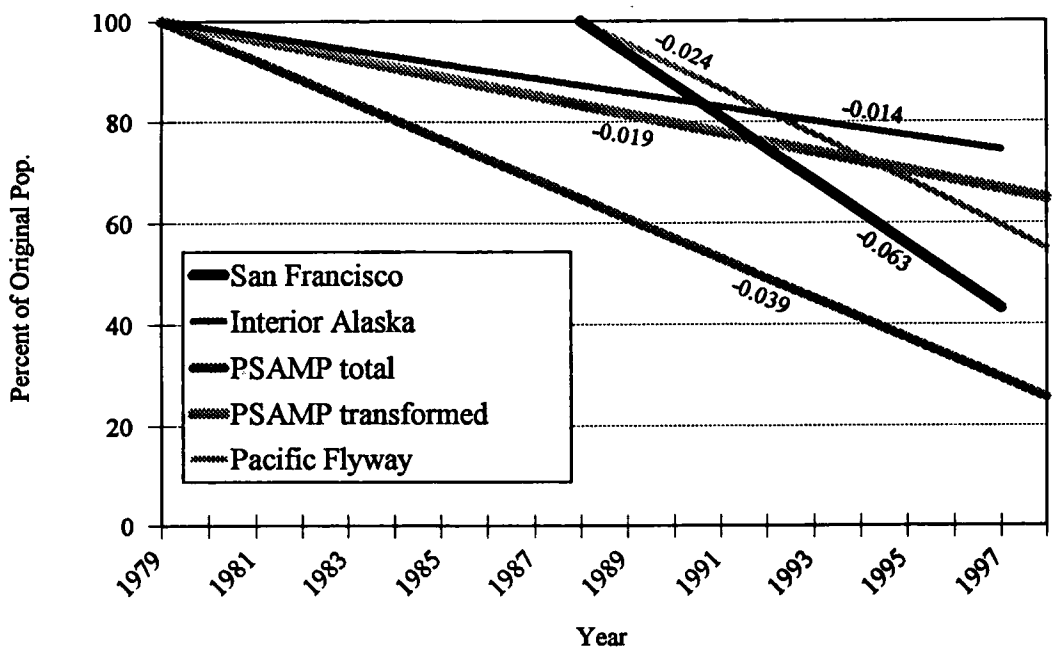


Figure 6. Trends in scoter populations in Alaska, Washington, and San Francisco Bay.

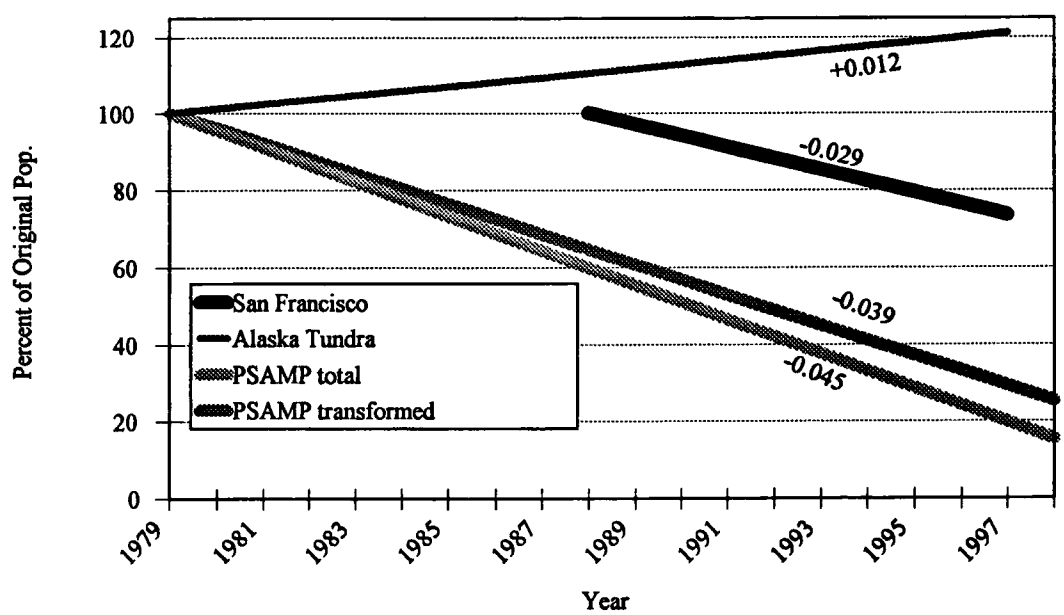


Figure 7. Trends in scaup populations in Alaska, Washington, and San Francisco Bay.

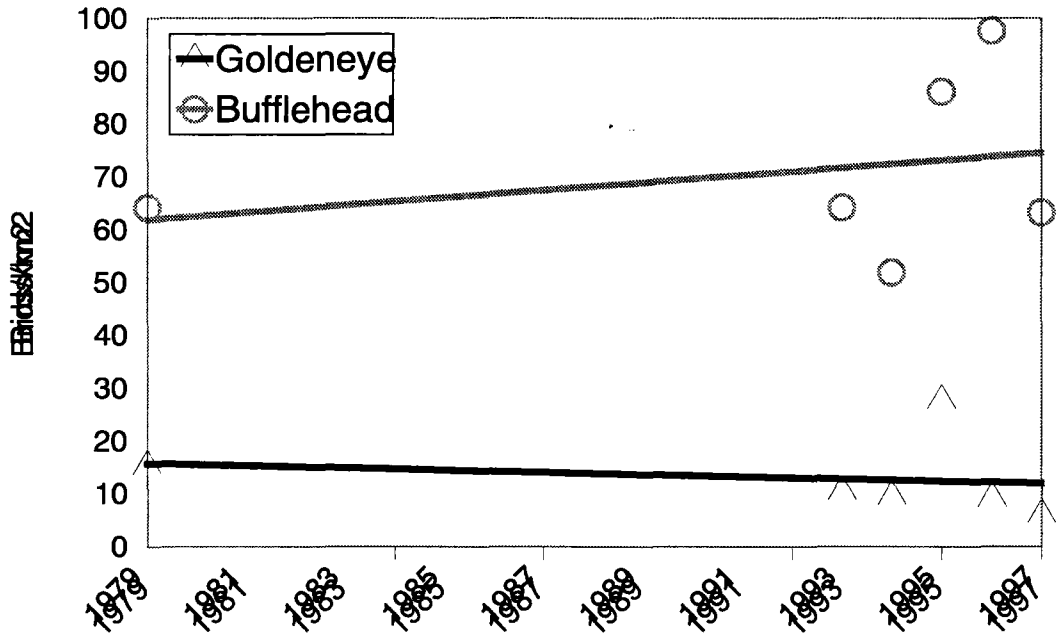


Figure 8. Densities of goldeneye and bufflehead between MESA (1978–79) and PSAMP (1993–98) for shared transects.

The initial design contract for the PSAMP surveys in Washington state also produced a digital database of the historical data available, primarily data associated with the MESA studies in 1978–79. This contract also provided software to develop indices with confidence limits. When this was utilized on both the recent PSAMP 1993–98 surveys and the MESA 1978–79 surveys, the results appeared to indicate that the decline might be in the range of 50–70% (Figure 9). This scoter decline should be used with caution, however, for when we examined the historical database and software developed to calculate population indices, two sources of error were discovered. The software was treating different survey methodologies equally in the comparison and calculations of population indices. The 1978–79 MESA surveys utilized three to four types of survey methods: surveys from either small boats or ferries, aerial surveys, and point counts from shore. The aerial survey method was the least emphasized of these, especially in near-shore areas. The aerial method was employed mostly in areas where access by land was limited, and in the open water regions where access by boat was more difficult. The 1992–98 PSAMP surveys only utilized the aerial method. It was also discovered that the software was not treating the data appropriately and is in need of corrections in the code.

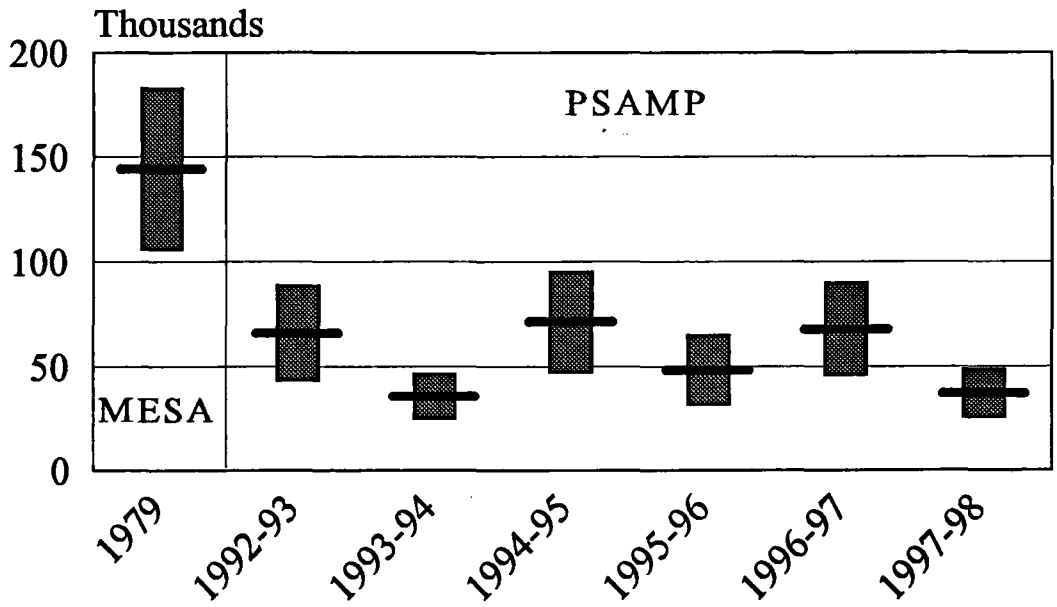


Figure 9. Comparison of winter scoter population indices (with 95% C.L.) in MESA areas using PSPOP Software, for MESA (1978–79) and PSAMP (1993–98) periods.

To come up with a more comparable way to assess changes in densities between the 1978–79 MESA surveys and the PSAMP surveys, those near-shore aerial transects flown in the MESA surveys that were comparable to the PSAMP transects were selected. Similar transects were found in 19 MESA sub-regions, comprising 65.56 km^2 surveyed during MESA transects, and 303.27 km^2 surveyed during PSAMP transects (Figure 10). Two methods were used to calculate densities for scoters and scaup from these data.

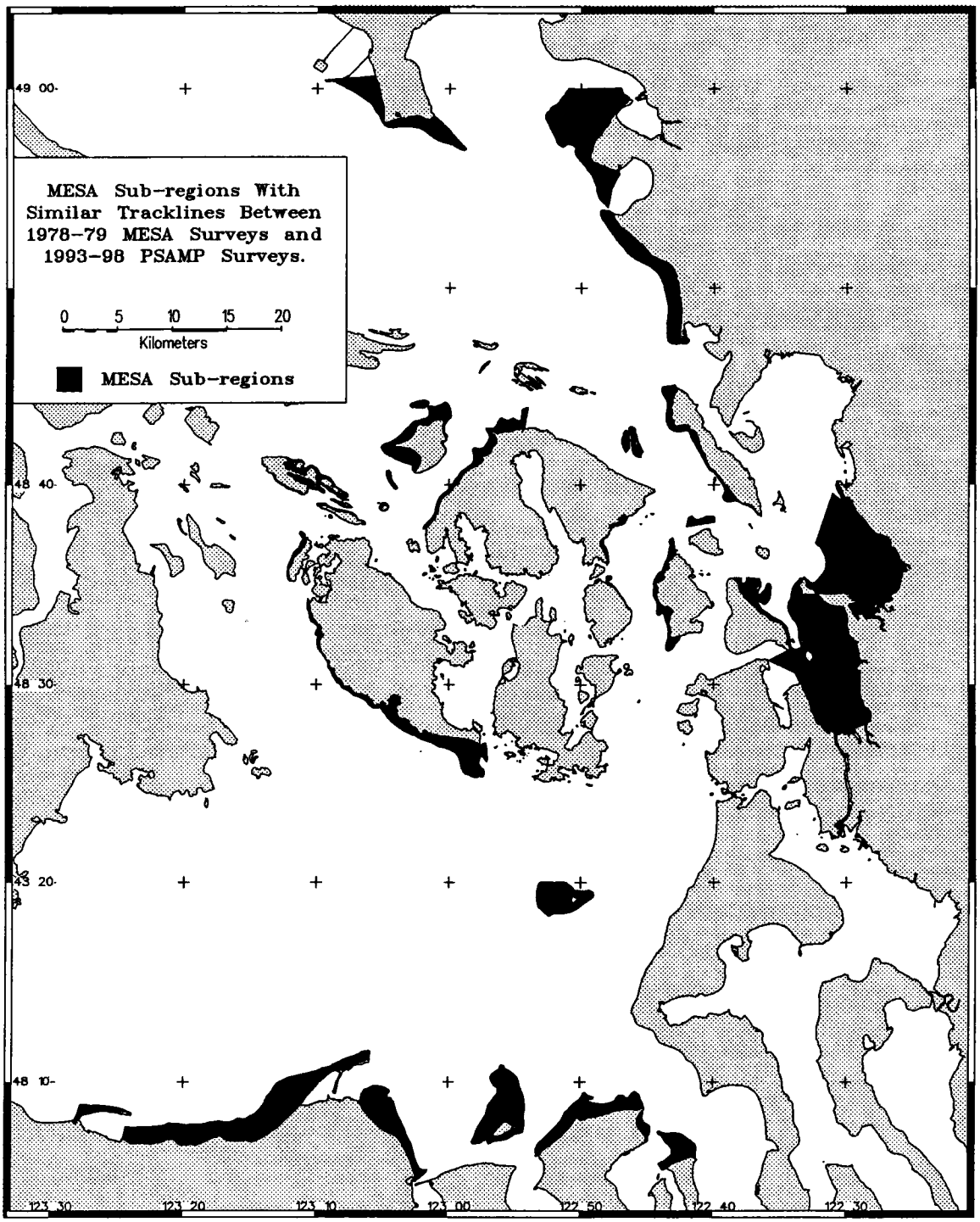


Figure 10. Areas with similar aerial transects flown in MESA and PSAMP time periods.

The first method calculated an overall density for each winter period (1978–79 MESA, and all six winter PSAMP surveys) from the total number of scoters and scaup divided by the total area covered by the transects the respective season. This method suggested a decline in scoter and scaup densities of 65.7% and 70.4%, respectively, over the 18-year period (Figure 11).

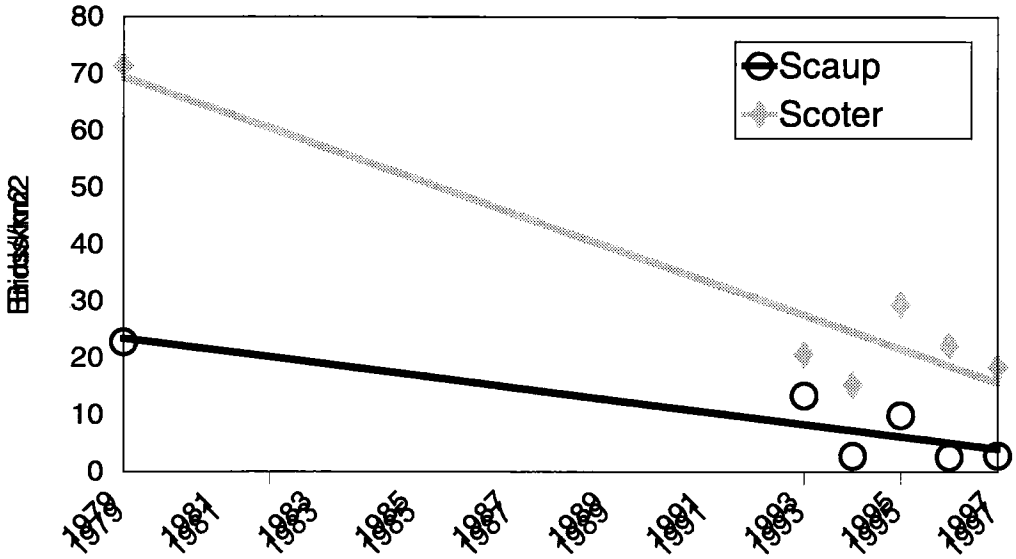


Figure 11. Decline of overall total densities of scoters and scaup on shared transects compared between MESA (1978–79) and PSAMP (1993–98) in greater Puget Sound.

The second method was used to determine estimated means of, and confidence limits for, scoter and scaup densities within the 19 MESA sub-regions. The data was combined into two periods: 1978–79 MESA transects (N=118 sample units) and 1993–98 PSAMP transects (N = 211 sample units). Densities for each sample unit were log-transformed. An estimated mean density, for each period, was calculated weighting by sample unit area, and then back-transforming the value of the mean logged density. Difference between the periods was tested by factorial ANOVA. This method presented a significant decrease in both scoter densities (P=0.024, 35.32% decline between periods), as well as scaup densities (P=0.000, 74.56% decline between periods). The slopes for annual change from the earliest estimated index is -0.019 for scoters and -0.039 for scaup using the transformed densities from the comparable transects (Figures 12 and 13; also Figures 6 and 7).

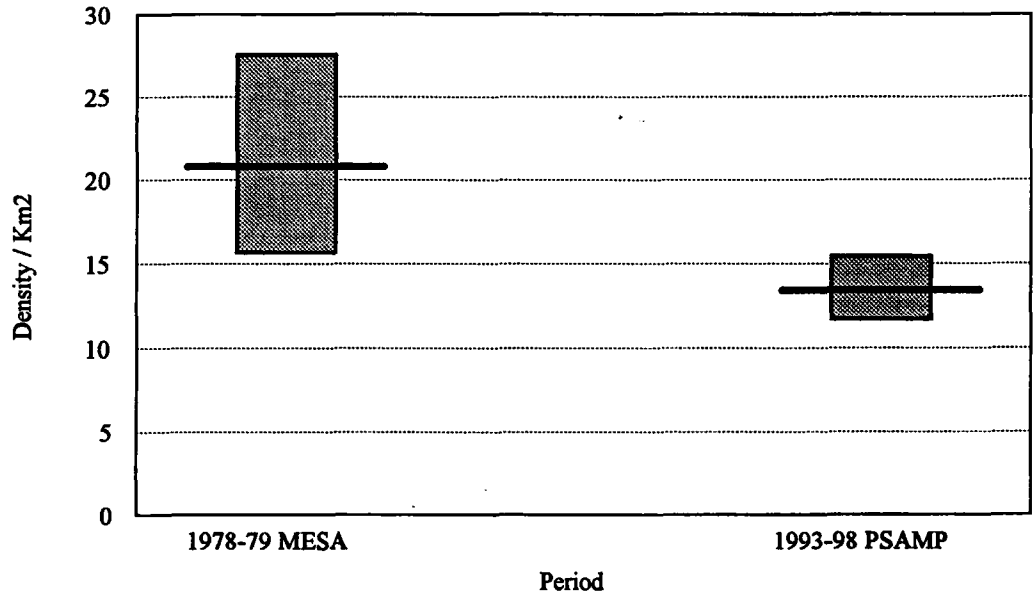


Figure 12. Comparison of estimated mean densities (with 90% confidence limits) of scoters for shared transects between MESA (1978–79) and PSAMP (1993–98).

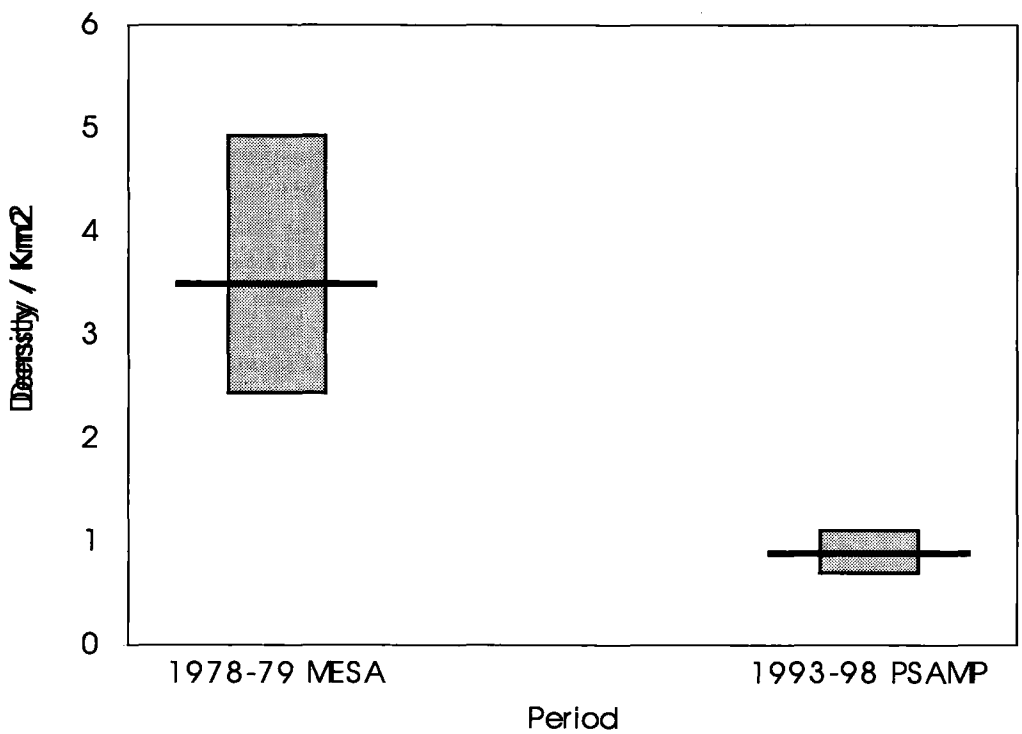
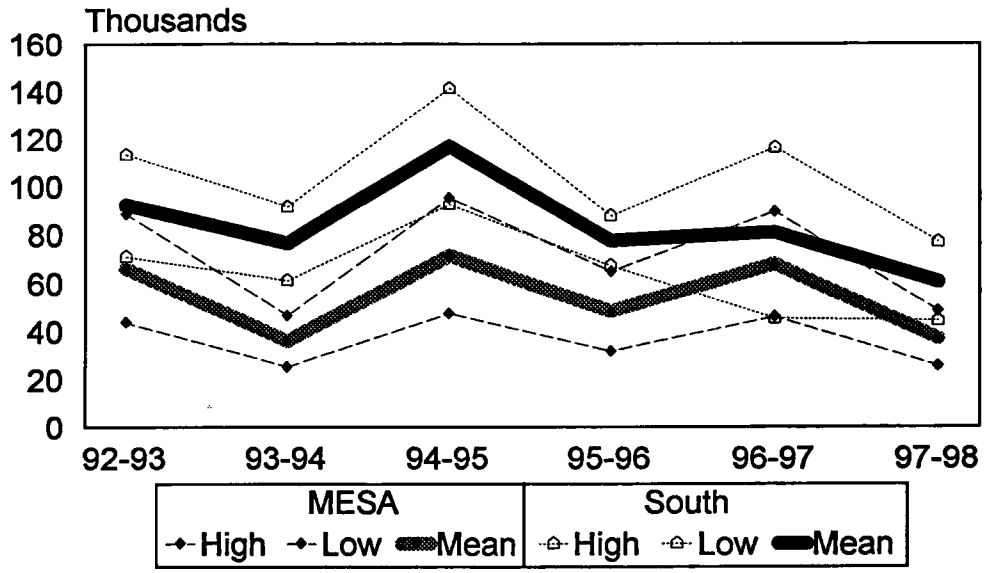


Figure 13. Comparison of estimated mean densities (with 90% confidence limits) of scaup for shared transects between MESA (1978–79) and PSAMP (1993–98).

In an effort to evaluate whether portions of the wintering scoter population may have moved from one portion of Puget Sound to another, we also compared the indices and confidence limits by MESA area versus the southern portions of Puget Sound for all years of the PSAMP surveys where all areas were covered by the survey (Figure 14). We utilized the indices calculated by the original contracted software, because we have not had a chance to redo these. Currently we are making the assumption that the relative changes would not be changed by new programs, but this analysis will be revisited when a new program is developed. At the present, it appears that any decrease or increase any one year in the MESA (northern) study area seems reflected by a similar change in the southern portion of Puget Sound. This suggests that local movement may not be a major factor in these declines.



Means (95% confidence limits) during December through February aerial surveys.

Figure 14. Comparison of scoter indices in winter during PSAMP surveys between northern (MESA study area) and southern greater Puget Sound.

San Francisco Bay

Scoter and scaup species are also important components of wintering diving ducks associated with San Francisco Bay. More intensive type surveys have looked at the open bays and salt ponds of San Francisco Bay between 1988 and 1997. The overall estimates that have been derived from this work are part of the midwinter waterfowl counts and were provided by Dr. John Takekawa, USGS, Biological Resources Division (Figure 15). Two caveats should be mentioned about this data: surf scoters make up 99% of scoters seen here, and both greater and lesser scaup are found here, although the greater scaup should still be more predominant in the marine settings. These data are either overall counts or estimates and are not displayed as means. Hence, for comparison sake, the degree of change displayed here may be most comparable to overall counts, indices, or densities for Puget Sound rather than the mean densities derived earlier.

Much higher numbers of scaup (by an order of magnitude) utilize San Francisco Bay than are found utilizing greater Puget Sound. Nevertheless, both scoters and scaup appear to be declining over the last ten years. We do not know if this same trend occurred during the previous decade, but the slope of annual change from the earliest estimated index (1988) is -0.026 for scaup and -0.057 for scoters over the last ten years (Figures 6 and 7).

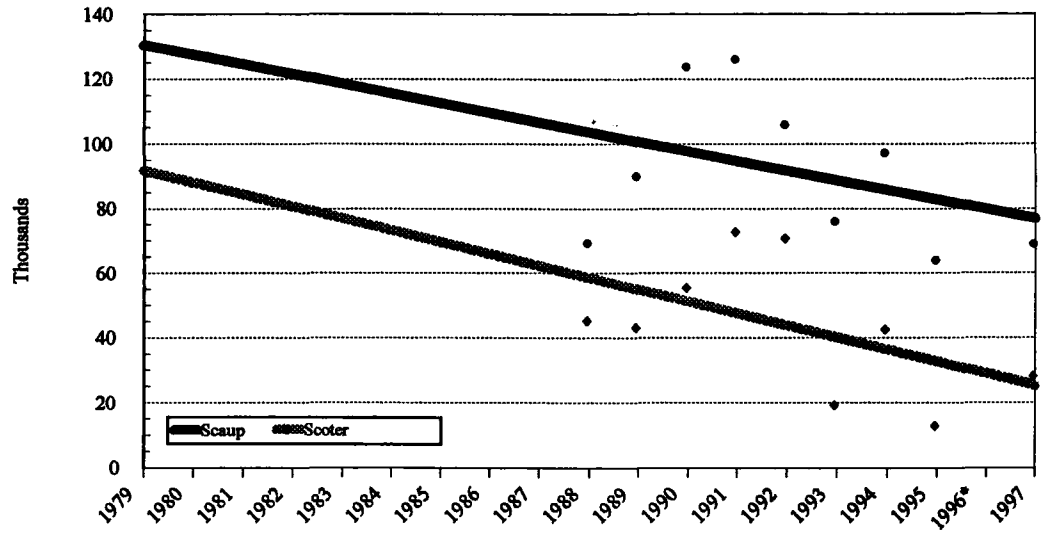


Figure 15. Scoter and scaup numbers in San Francisco Bay midwinter censuses 1988–1997 (Takekawa pers. comm. 1998). Note: open bays and salt ponds were not surveyed in 1996.

Lower Columbia River

The lower Columbia River and estuary are somewhat different from San Francisco Bay and greater Puget Sound in that the waters are more influenced by fresh water and river dynamics than by marine conditions. Hence this estuary appears to be more attractive to scaup than to scoter,s and it may include larger percentages of lesser scaup which may be undergoing different dynamics than the greater scaup population. The estuary is also much smaller in size. There is less of a consistent survey approach that is comparable to that conducted in recent years in both San Francisco Bay and greater Puget Sound (i.e., the PSAMP protocols and aerial surveys). At the present time we were only able to look at data for 1993–98 that was relatively consistent in its survey scope.

Scoters are consistently present only in low numbers (<1000) as are most other marine diving duck species like bufflehead and goldeneyes (Figure 16). The lower Columbia River may be used during migration by scoters for short periods as they move up the coast, but it does not serve as a wintering ground for large concentrations of and hence gives us no added perspective on changes over time. Scaup use of the lower Columbia differs from that of scoters, with numbers usually in the 5,000 to 13,000 range with one peak reaching almost 21,000 in 1996, equal to or greater than that observed recently in greater Puget Sound during any annual PSAMP survey. However, as most of the scaup observed in the lower Columbia were present in the most upstream portion of the estuary, it is unclear which species (lesser or greater scaup) comprise these numbers since this is probably the more fresh water portion of this estuary which lesser scaup prefer. At any rate, the declines in both greater Puget Sound and San Francisco Bay overwhelm any temporary increase seen one year in the lower Columbia River.

Other Wintering Areas

Significant numbers of scoters winter (in differing species compositions) in British Columbia, southeast Alaska, and other portions of Alaska (i.e., Kodiak Island). Some estimates of populations have been made, but trend data is not available as yet for these areas to the best of our knowledge. Conant et al. (1988) estimated through aerial surveys and correction factors that 51,256 scoters (±69%), but only 283 scaup (±156%), probably winter in the northern half of southeast Alaska. Aerial surveys in British Columbia (Vermeer et al. 1983) counted 33,477 scoters January–February on 7,138 km of transects throughout much of the marine coastal habitat; they estimate that half the birds

present were observed (Savard 1982). Forsell and Gould (1980) estimated that 35,000 white-winged scoters, 5,000 surf scoters, and 3,750 scaup wintered in the Kodiak Island area. It is uncertain from available data whether decreases in some areas might have been balanced out by changes in these other wintering areas, but the 1997–98 fall and winter waterfowl survey report for the Pacific flyway (Trost 1998) lists overall numbers for scoters on wintering areas 1988–98 that suggest declines are occurring throughout the flyway (Figure 17).

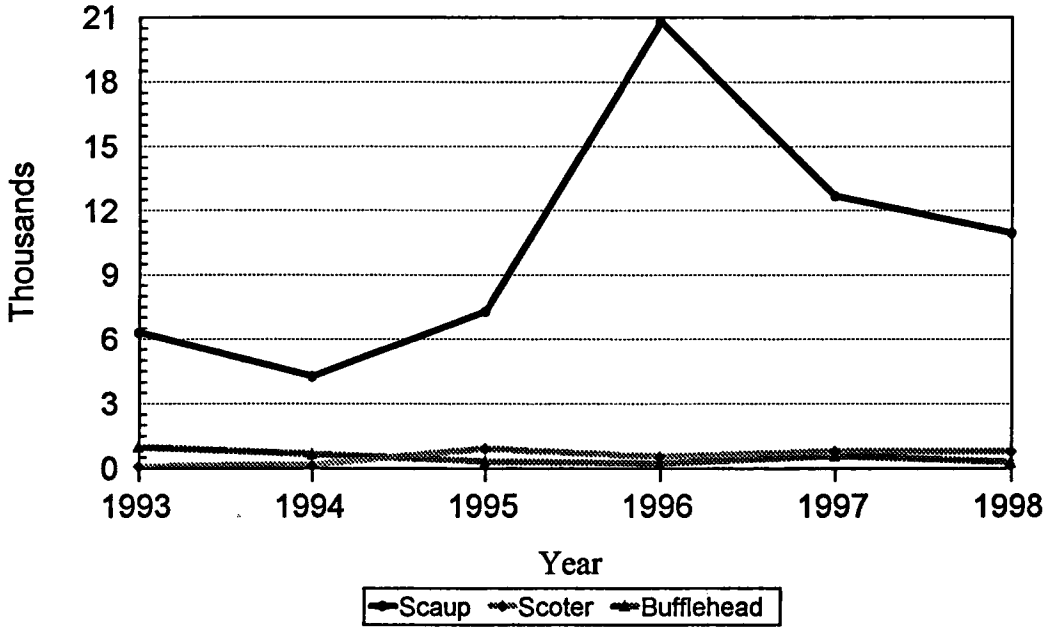


Figure 16. Scaup, scoter, and bufflehead numbers in lower Columbia River estuary midwinter censuses 1993–98 (Kraege unpub. data).

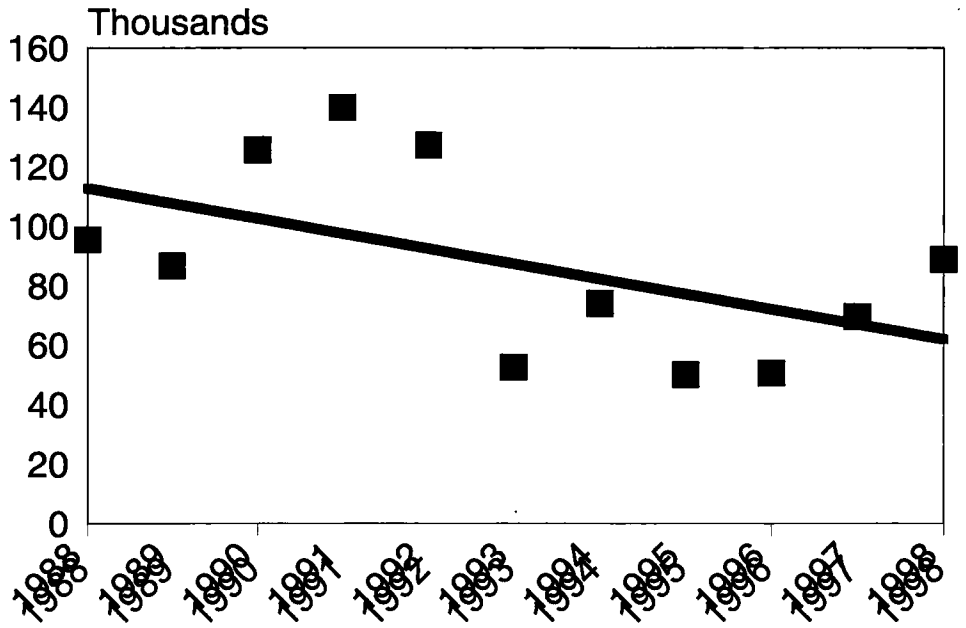


Figure 17. Trends in scoters from midwinter censuses in Pacific Flyway 1988–98 (Trost, R.E. 1998).

Alaska Breeding Estimates

Major breeding concentrations of ducks in Alaska have been consistently monitored each summer since 1957 with strip transect sampling from aircraft (Hodges et al. 1996). Starting in 1977, these surveys switched to a different type of aircraft, and since then the surveys have followed the same protocol. Scoter observations include all three species and scaup sightings combine two species whenever they were encountered. However, the Alaskan surveys can be separated by areas. Interior or taiga portions would include only surf and white-winged scoters whereas the coastal or tundra areas include all three species of scoters. Conversely, the tundra or coastal scaup are primarily the greater scaup. Little is known about what interchange may occur between years between areas. Surf scoters may or may not move between the coastal and interior portions of Alaska any one year. We are making the assumption that it is more comparable to choose an area that has no black scoters to compare with what is seen in western Washington marine waters, where black scoters are not abundant.

Hodges et al. (1996) suggested that the populations of diving ducks (*Aythya* spp.) and sea ducks (*Bucephala* spp. and *Melanitta* spp.), except those of mergansers (*Mergus* spp.) and canvasback (*Aythya valisineria*), declined by 15–75% during 1976–94. Data recently obtained that includes the last three years (Hodges, pers. comm.) portrays a recent upswing in both scoters and scaup in portions of their breeding range, thereby reducing or eliminating some of the decline documented earlier. In spite of this, scoters continued to decline in interior Alaska by 23.8% over 18 years, a slope from original estimate of -0.013 (Figures 6 and 18), while the tundra scaup increased by 10.4% over 18 years, a slope of +0.006 (Figure 7 and 19). In the case of scaup in Alaska, the total numbers estimated greatly exceed any total found in greater Puget Sound and San Francisco Bay combined. This finding suggests that the Alaska population either 1) contributes to several different American or Asiatic flyway populations, 2) experiences considerable mortality before they arrive in wintering grounds, or 3) the breeding surveys in Alaska included populations moving through to eastern Siberia or other portions of their breeding range. Scaup populations in North America have declined since the mid-1980s, and do not appear to be responding to current improvements in water conditions on the breeding grounds (Allen and Caithamer 1998). Hence, the larger numbers estimated in Alaska stand in contrast to some of the evidence gathered elsewhere in North America.

Conclusions and Concerns

Pacific Flyway

- Significant declines are being recorded in portions of the Pacific flyway for at least two species groups of diving ducks commonly found in greater Puget Sound: scoters and scaup.
- The rate of decline in the wintering areas of Puget Sound and San Francisco Bay for both scoters and scaup are equal to or greater than those recorded in the Alaska breeding grounds.

Greater Puget Sound

- The wintering populations of scoters have declined significantly since 1978. The exact rate of decline can be debated, but by all estimates or indices the declines are accumulating to sizable proportions as the decline continues over an ever-increasing period of years.
- Bufflehead and goldeneyes have not exhibited this same pattern of decrease in wintering populations using greater Puget Sound, but have demonstrated either a stable or slightly increasing trend.

Dramatic declines in numbers of scoters and associated stocks of herring spawners have demonstrated many similarities in timing and scale (Figure 20). Scoters have historically moved in late winter and early spring to concentrate in large numbers near forage fish spawning occurrences like Cherry Point (Wahl et al. 1981), and would feed on the concentrations of roe just before migrating north to breeding grounds. This phenomena in March and April has not been monitored in recent years. It seems probable that this spring

concentration of scoters would show at least similar declines to those documented for scoters in wintering areas like greater Puget Sound.

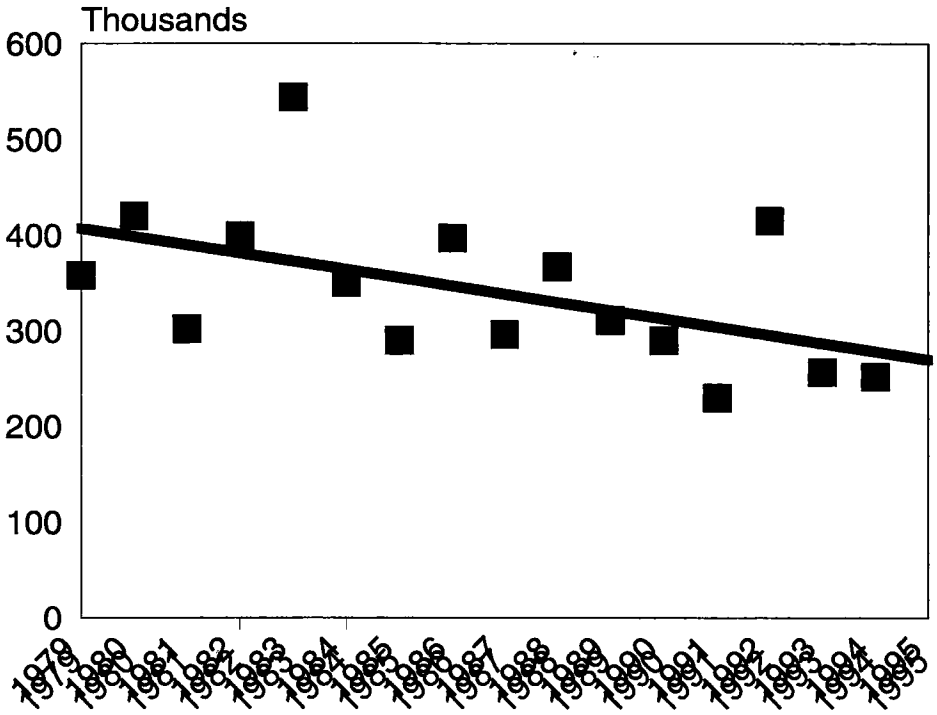


Figure 18. Trends in scoters estimates in interior Alaska observed by summer aerial surveys 1979–97 (Hodges et al. 1996). Note: By choosing only interior Alaska scoter surveys, the focus is on the same two primary scoter species found in Washington.

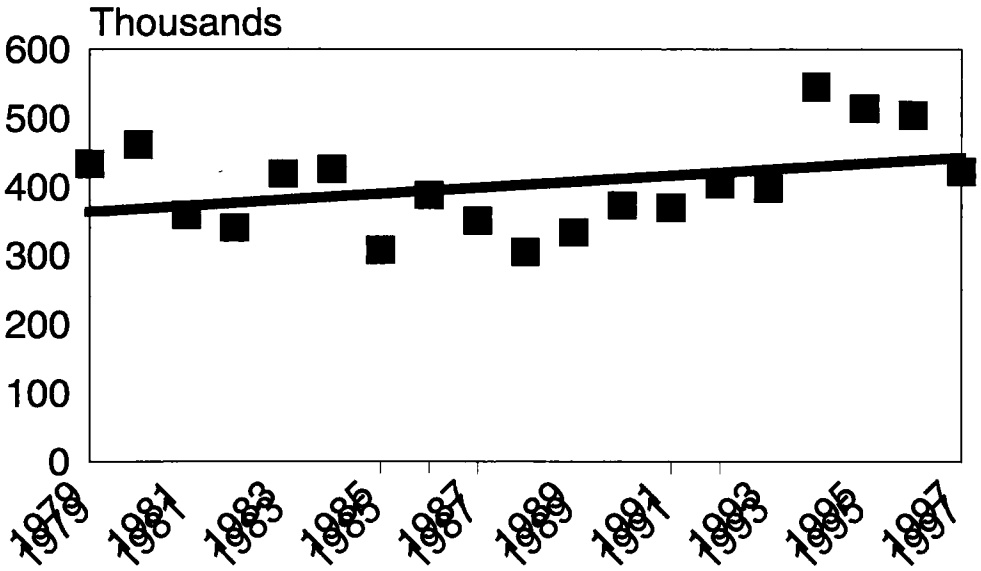


Figure 19. Trends in tundra scaup estimates in Alaska seen on summer aerial surveys 1979–97 (Hodges pers. comm. 1998).

- Scoters and scaup differ in their distribution and habitat use in Puget Sound. Scoters are often

seen where scaup are located, but scaup are not always located where there are scoters. This may be due in part to the fact that scoters are more numerous than scaup, but it may also reflect a different use of marine habitats in Puget Sound. The PSAMP surveys observed goldeneyes and buffleheads pursuing different patterns of habitat usage than those observed for either scoters or scaup. These differences were similar to those documented earlier in Puget Sound for wintering sea ducks (Hirsch 1980). In Hirsch's study, different sea duck species overlapped in their usage of the nearshore marine habitats, but the different species varied from each other in terms of food types sought, foraging style utilized, and portion of the nearshore habitat searched for food items.

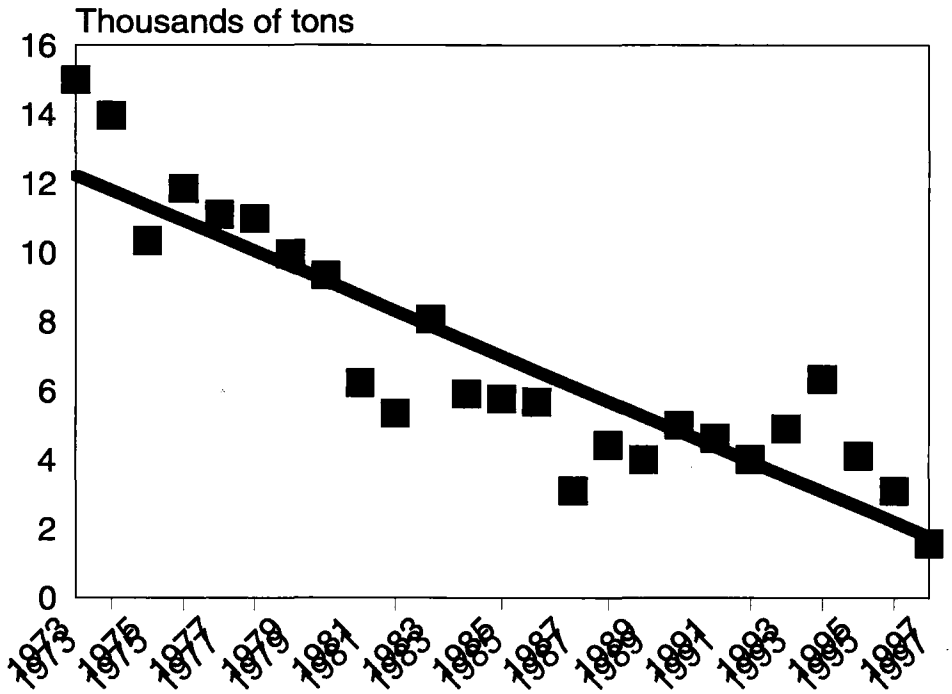


Figure 20. Trends in herring spawning estimates at Cherry Point, Washington 1979–97.

Implications of this Work

This component's efforts have concentrated on monitoring numbers and distribution of marine birds, their patterns of habitat usage, and trends in these factors over time. None of the decreases evaluated in this paper would have been perceived without a commitment to a long term series of standardized monitoring. The longest survey effort (Alaska breeding grounds) has been the most effective in documenting both greater and lesser degrees of change. It is important to keep monitoring efforts continuing at both wintering and breeding grounds if we are to be able to recognize and evaluate trends over time, but research concerning causes might consider some of the following topics for hypotheses to examine.

Contaminants

Scoters have been known to accumulate contaminants during their stay at wintering grounds (Henny et al. 1991). Two recent studies concerning surf or white-winged scoters in the Pacific flyway (Henny et al. 1995 and Mahaffy et al. 1997) did not clearly implicate nor eliminate contaminants in terms of some role that they may play in the mortality and decreases of scoters recorded recently. However, the sample size is very small and little is known about the levels of contaminants required to cause deleterious effects in these diving duck species.

Breeding Ground Factors

Failures at the breeding grounds have been documented preliminarily for scoters (Henny et al. 1995), but causes have not been determined. Harvest by hunting does occur both in the spring and fall in or near the breeding areas in Alaska. Documentation of this is incomplete, but subsistence harvest in Alaska was estimated in 1996 to include 17,593 scoters (Paige and Wolfe 1997). It is unclear whether this is considered normal or exceptional. Much of the harvest is by natives and has been under-reported in the past.

Migration Stressors

Unusual mortality was documented during August 1990, 1991, and 1992 for molting adult scoters in southeast Alaska (Henny et al. 1995). Population stability of sea ducks is dependent on high adult survival and a few successful years of reproduction (Goudie et al. 1994). The mortality in southeast Alaska is not compatible with this reproductive strategy, and suggests something is stressing populations of scoters frequenting the Pacific flyway.

Wintering Conditions

The decrease in scoter numbers in the wintering areas appears to be equal to or greater than those recorded for the breeding areas. This suggests that wintering factors might be at least part of the causes behind declines. Since there is no demonstrated movement between areas of greater Puget Sound and other wintering areas of the Pacific flyway that would account for the decreases, the following would be potential categories to examine concerning changes on the wintering grounds:

- Habitat changes;
- Food web changes; or
- Effects from any one or combination of the three climate changes or cycles that influence the Pacific flyway (El Niño, North Pacific Decadal Oscillation, and the 1979 climate shift in North Pacific).

Implications for Other Species and Management

- Scoters are considered environmental indicators that can help in evaluating the health of Puget Sound because of their widespread occurrence and their consumption of several different components of the food chain: shellfish and eggs of forage fish at spawning concentrations of forage fish like herring.
- Other species of concern, like harlequin ducks, depend upon roe from the forage fish spawning concentrations that occur during spring in British Columbia and Washington (i.e., Denman and Hornby Islands in the Strait of Georgia). If changes in spawning forage fish stocks turn out to be key factors in scoter declines, it would appear likely that these reductions of forage fish may well tie in with other declines for other species.
- The Strait of Georgia and the northern half of the greater Puget Sound make up the same ecosystem and can not be managed or understood well without integrated monitoring, research, and analysis.
- The same food chains that support these migratory bird populations also sustain both anadromous and non-anadromous fish as well as marine mammal and bird populations. This correspondence must be addressed via some unified approach, which should include the management of commercial and subsistence harvest by humans.

Acknowledgments

Projects of this scope depend upon a wide variety of people for help to succeed and this project owes thanks to many. Dave Nysewander, Joe Evenson, Bryan Murphie, and Tom Cyra are the present project staff conducting these surveys, but Warren Michaelis, Janet Stein, Matt Nixon, Wendy Parsons, and Howard Ferguson played key roles in the projects at different times in the past. All deserve thanks and credit for their contributions.

The design and formation of this project in its early stages owes much to efforts of Lora Leschner, Don Kraege, and others. Glenn Ford at Ecological Consulting Inc. helped create and establish the computer programs needed. The Puget Sound Water Quality Action Team are thanked for their review and continuing support. The skills and cooperation of numerous state and commercial pilots were critical for the aerial surveys to be completed under winter conditions. We would also like to acknowledge the WDFW aircraft program, as well as Sound Flight and Puget Sound Seaplanes for their continued support providing the aircraft and pilots necessary for this project.

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Abundance and Distribution of Porpoise and Other Marine Mammals of the Inside Waters of Washington and British Columbia

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Introduction

The inside marine waters of Washington and British Columbia are highly productive, supporting a rich diversity of habitats and animal life, including nine species of commonly occurring marine mammals (Osborne et al. 1988; Calambokidis and Baird 1994). Three of the marine mammals, harbor seals (*Phoca vitulina richardsi*), harbor porpoise (*Phocoena phocoena*) and to a lesser extent, Dall's porpoise (*Phocoenoides dalli*), are vulnerable to entanglement in gillnets (Stacey et al. 1990, 1997; Gearin et al. 1995; Barlow et al. 1995a; Pierce et al. 1996).

The National Marine Fisheries Service (NMFS) is responsible for reducing human-caused marine mammal mortality below levels deemed to be significant based on abundance estimates within U.S. waters (Barlow 1995b). However, the marine mammals of this region undoubtedly use both U.S. and Canadian inside waters and are affected by national, provincial and state regulations. Therefore, the National Marine Fisheries Service (NMFS), National Marine Mammal Laboratory, Washington, in cooperation with the Department of Fisheries and Oceans, British Columbia, was interested in estimating abundance for these three species in this entire inside water region.

For the inside waters of Washington and British Columbia, data on harbor porpoise and Dall's porpoise is insufficient to determine the effect of incidental takes on their population size. The harbor porpoise abundance estimates are either outdated (Calambokidis et al. 1992) or do not include most of these inside waters (Flaherty and Stark 1982; Osmek et al. 1995). Dall's porpoise abundance estimates are lacking except for one area in Puget Sound (Miller 1989). Recent estimates of harbor seal abundance exist for U.S. (Jeffries et al. 1997) and most of British Columbia inside waters (Olesiuk et al. 1990; Olesiuk In prep.).

We report the preliminary results of aerial surveys for marine mammals that cover the inside waters of Washington and British Columbia (see Calambokidis et al. 1997). Additional analyses of these data are still underway and will be compared to a re-analysis of the 1991 survey data (Calambokidis et al. 1992) to determine possible trends in harbor porpoise and Dall's porpoise abundance. The objectives of this study were to estimate abundance of harbor porpoise and Dall's porpoise and to examine the geographic distribution of these species plus harbor seals. Data on harbor seal and porpoise distribution is used to evaluate whether certain areas of high sighting rates might be identified as locations to be avoided by fisheries known to incidentally take these species in their gill nets (see Pierce et al. 1996).

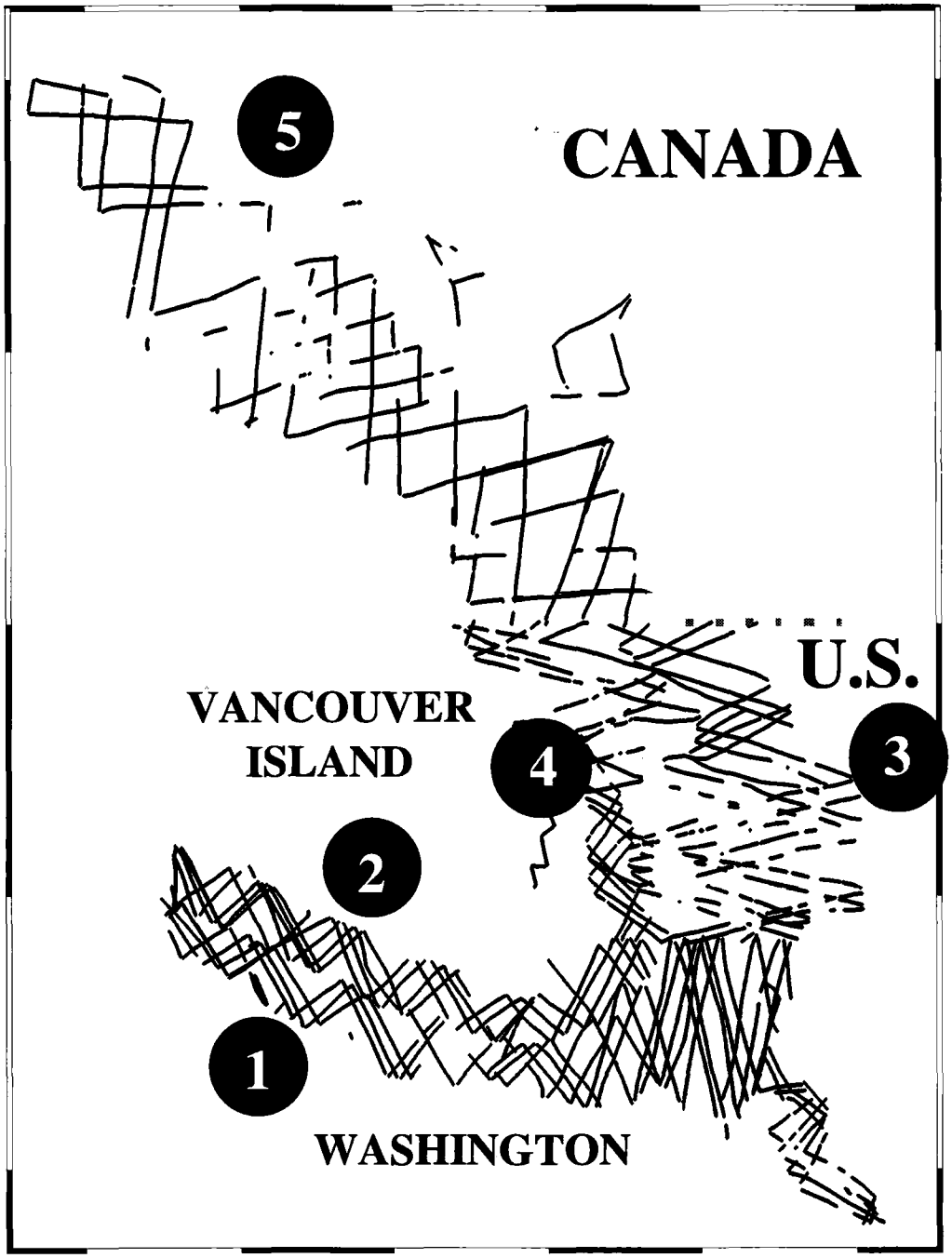

Figure 1. Study area and on-effort survey transects (bold lines). The five regions, (1) U.S. Strait of Juan de Fuca, (2) Canadian Strait of Juan de Fuca, (3) U.S. San Juan Islands, including Admiralty Inlet, (4) Canadian Gulf Islands, and (5) the Strait of Georgia (49°N to 50°), were flown under acceptable visibility conditions of Beaufort level ≤ 2 and cloud cover ≤ 25%.

Methods

Study Area

The 1996 study area included the inside waters of Washington and British Columbia within latitudes 47°53' N to 50° N and the western entrance of the Strait of Juan de Fuca (124.44° W) (Figure 1). This western edge of the study area is the line extending from Tatoosh Island, WA to Bonilla Point, BC, a boundary used by NMFS to define and manage two harbor porpoise stocks (Osmek et al. 1996). The study area was divided into five separate regions based on water bodies and the international border: 1) U.S. Strait of Juan de Fuca (2,971 km^2), 2) Canadian Strait of Juan de Fuca (2,137 km^2), 3) U.S. San Juan Islands, including Admiralty Inlet (1,531 km^2), 4) Canadian Gulf Islands (1,350 km^2), and 5) the Strait of Georgia (49° N to 50° N; 6,370 km^2). Surveys of Hood Canal and Puget Sound proper (south and east of Whidbey Island) were not flown because harbor porpoises densities were known to be extremely low (Calambokidis et al. 1992; Osmek et al. 1995).

Survey Design and Data Acquisition

From 7–22 August 1996, a total of 6,263 km of aerial line transect surveys were conducted following a saw-tooth design (Cooke 1985) from a high-wing (Partenavia P-68) twin engine aircraft flying at an altitude of 183 m (600 ft) and a speed of 167 km/hr (90 kts). Every minute, and whenever a sighting occurred, the aircraft position was automatically recorded on a laptop computer connected to a GPS. Beaufort wind scale (sea state) and percent cloud cover was entered at the beginning of each transect and when visibility conditions changed. Five unique replicate survey lines were flown in all areas except the Strait of Georgia, where three replicates were flown.

Sighting data were acquired by three observers, located at each side bubble window and the belly window and was entered in to the computer by the recorder located in the copilot's position. Sighting data included species, group size, presence of young animals, and clinometer angle measured from the aircraft to the group as it passed abeam of the aircraft. This measurement was used to calculate the distance from the trackline and to more accurately estimate the position for each sighting. Most groups were sighted within 400 m of the trackline.

Water depth data were determined for all sightings and one-minute aircraft positions using nautical charts published by the U.S. National Oceanic and Atmospheric Administration and Canadian Hydrographic Service, Department of Fisheries and Oceans. Chart scale ranged from 1:40,000 to 1:80,000 in U.S. waters and was 1:80,000 in Canadian waters. Depths were interpolated to the nearest meter or fathom. Due to the large sample sizes of harbor seals and aircraft positions, every fourth harbor seal sighting and every other aircraft position were measured and subsequently used to calculate mean depth. The one-minute aircraft positions were considered an unbiased estimator of effort because the recorded location was independent of the waypoint positions used to define the flight path.

Geographic Distribution

Geographic cells, measuring 10 minutes latitude (18.5 km) by 15 minutes longitude (19 km) (352 km^2), were defined throughout the study area and sighting rates were computed (groups/100 km). To ensure a sufficient number of sightings per cell, we only used a minimum of 40 km of aerial effort for the porpoise cells and 20 km for harbor seal cells.

A 2-way ANOVA was used to analyze sighting rates (animals/km) differences by depth and region. Samples consisted of pooled transect segments from each replicate survey in a region that were conducted within a specific depth class of each region under acceptable sighting (weather) conditions. Only samples with a minimum of two "one-minute" effort positions (representing an average of at least 5 km) were used in the depth analysis to reduce variation from minimally sampled strata. All statistical tests were conducted with a 0.05 significance level.

Density and Abundance Estimation

We statistically tested differences in the number of animals seen per kilometer of survey effort among regions, Beaufort sea state, percent cloud and year using an analysis of covariance (ANCOVA) procedure similar to that employed by Forney et al. (1991). Samples consisted of pooled transect segments from each replicate survey in a region that were conducted under acceptable weather conditions under similar visibility conditions (Figure 1). The results of the analysis indicated that only data collected under the best conditions of sea state (Beaufort ≤2) and cloud cover (≤25%) should be used in order to reduce bias. A total of 4493 km of total on-effort survey trackline was retained and used to determine abundance.

Table 1. Survey regions, effort and preliminary sighting rates during 1996.

	Area	Effort	Harbor porpoise			Dall's Porpoise		
Region	(km^2)	(km)	Sightings	Animals	Sight rate	Sightings	Animals	Sight rate
U.S. Strait of Juan de Fuca	2,971	1,365	90	127	0.066	29	49	0.021
U.S. San Juan Islands	2,137	752	58	83	0.077	11	15	0.015
Canadian Strait of Juan de Fuca	1,531	728	60	86	0.082	11	20	0.015
Canadian Gulf Islands	1,350	546	31	44	0.057	13	28	0.024
Strait of Georgia	6,370	1,102	20	23	0.018	0	0	0.000
Total	14,359	4,493	259	363	0.058	64	112	0.014

Density and abundance estimates were calculated with the computer program DISTANCE (Laake et al. 1993) and the methods described in Burnham et al. (1980) and Buckland et al. (1993). DISTANCE was used to select the best model for the probability density function fit to the perpendicular distances, calculate f(0) and its variance, and to test for relationships between group size and distance from the transect line. Abundance was calculated as:

$$N_r = \frac{n_r * E(S_r) * f(0) * g(0) * A_r}{2L_r}$$

where $\mathbf{N_r}$ denotes estimated abundance in a region, **r** = one of five regions, $\mathbf{n_r}$ denotes sightings in a region, $\mathbf{E(S_r)}$ = group size for that region, **f(0)** = the probability density function at distance zero, **g(0)** = the probability that an animal is detected on the trackline, and $\mathbf{L_r}$ is the distance surveyed in region, and A_r is the area of the region. A g(0) of 0.292, (CV=36.6%) was used based on calibration surveys conducted in the San Juan Islands in 1992 (Laake et al. 1997) which used the same aircraft and survey procedures employed in this study.

Estimates of variation for the regional abundance estimates were defined using:

$$cv(N_r) = \left[\left(cv(n_r)\right)^2 + \left(cv(E(S_r))\right)^2 + \left(cv(f(0))\right)^2 + \left(cv(g(0))\right)^2 \right]^{\frac{1}{2}}$$

The variance for n_r was calculated based on the replicate surveys conducted in each area (Buckland et al. 1993, p. 90). Pooled estimates of abundance were calculated as the sum of the regional estimates.

Results

A total of 1,505 sightings of 3,340 animals from nine marine mammal species were sighted during the on-effort portions of the two-week survey (Figure 2). The three most common species were harbor seals, harbor porpoise, and Dall's porpoise, accounting for 71%, 22% and 6% of all sightings, respectively. Other species sighted under acceptable visibility conditions were killer whales (n=8) (*Orcinus orca*), gray whales (n=3) (*Eschrichtius robustus*), minke whales (n=2) (*Balaenoptera acutorostrata*), Steller sea lions (n=3) (*Eumetopias jubatus*), California sea lions (n=1) (*Zalophus californianus*), and sea otters (n=3) (*Enhydra lutris*) (Figure 3). No marine mammals other than harbor seals and harbor porpoise were sighted in the Strait of Georgia.

Number of Marine Mammal Group Sightings

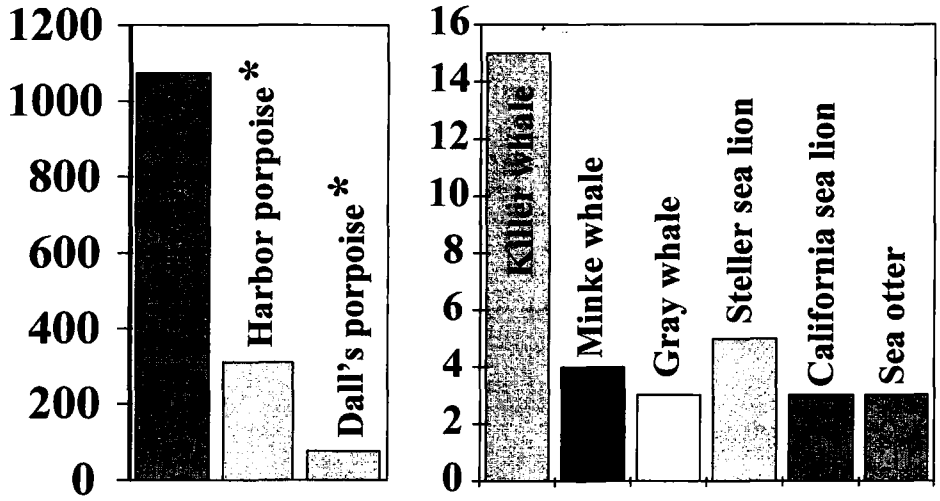

Figure 2. A total of 1,505 sightings of 3,340 animals from nine marine mammal species were sighted during the on-effort portions of the two-week survey. The tree most common species were harbor seals, harbor porpoise, and Dall's porpoise, accounting for 71%, 22%, and 6% of all sightings, respectively. Abundance estimates were calculated for the two porpoise species(*).

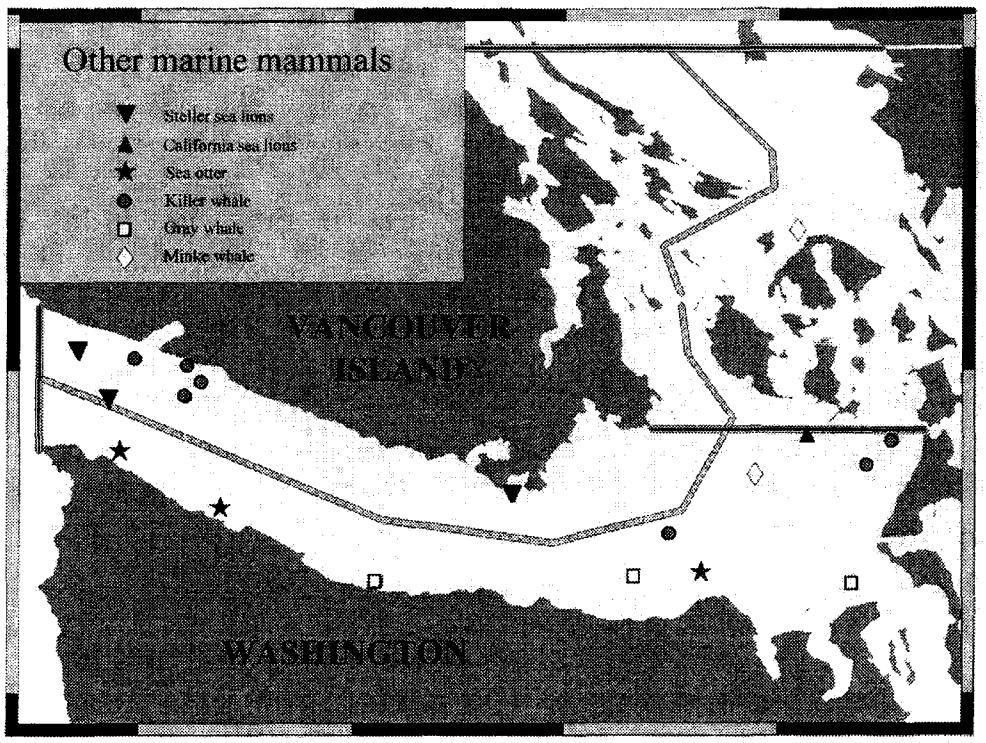

Figure 3. Locations of the other marine mammals seen during the 1996 surveys of the inside waters of Washington and British Columbia, Canada.

Harbor Seals

Sightings and Geographic Distribution

Harbor seal sightings were common and occurred throughout the study area in the narrow passages as well as in open water (Figure 4). A total of 862 groups (974 seals, including 20 pups) were observed at sea, while 26 groups (1,159 animals) were hauled out at various land sites.

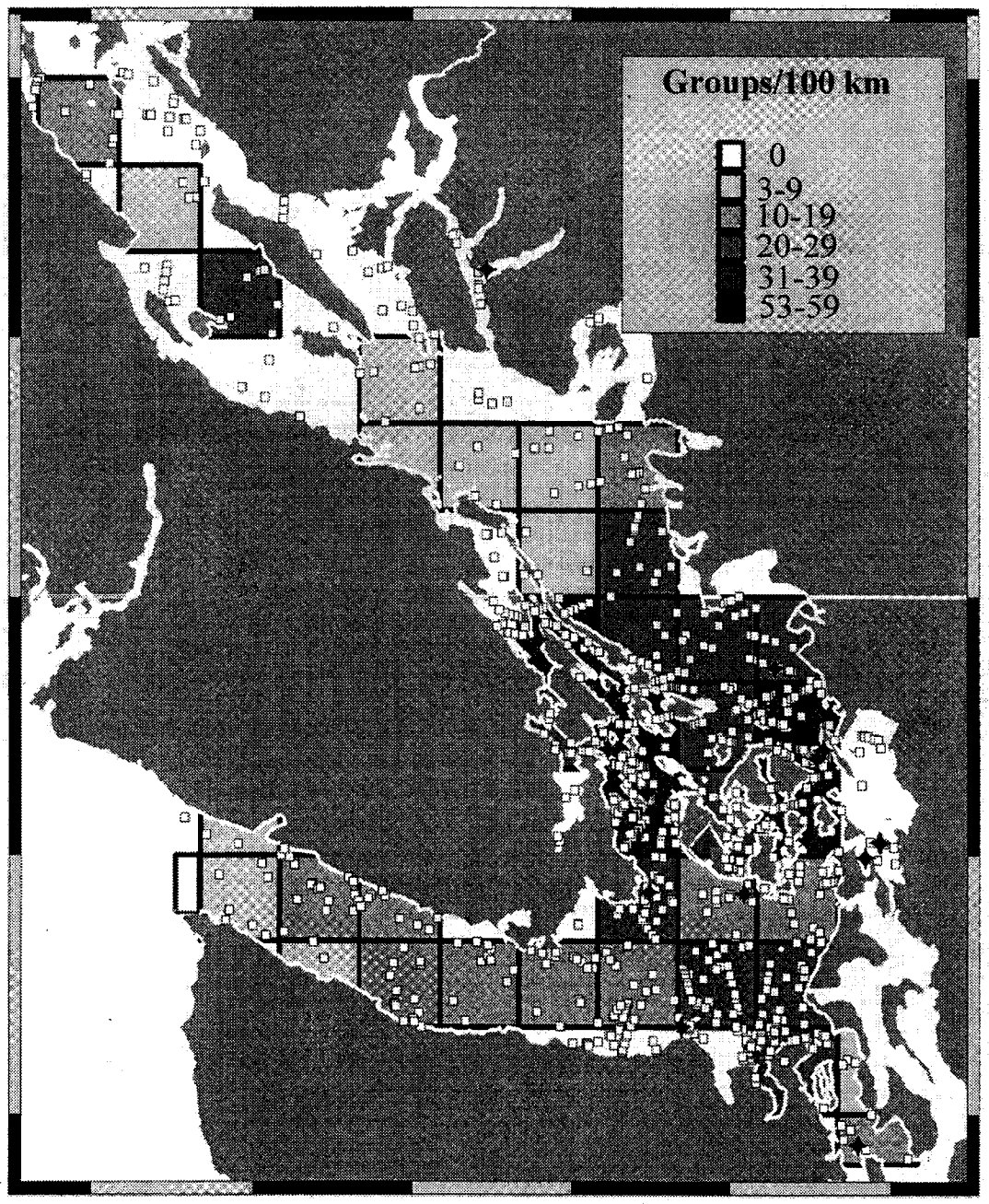

Figure 4. On-effort sightings of harbor seals and haul sites made under acceptable visibility conditions. Also shown are effort-corrected sighting rates (at sea) of harbor seals for geographic cells (352 km^2). A minimum of 20 km of aerial effort was required for each cell to ensure an adequate number of sightings were available for comparison with other cells.

Harbor seal sighting rates varied significantly by region and depth (2-way ANOVA, $P<0.05$). Sighting rates were highest in the two island regions of the (29.5–33.7 groups/100 km) and similar in the others (13.1–16.4 groups/100 km). Although harbor seals were sighted most in the shallower waters of each region (Figure 5), this species occurred in all depth classes.

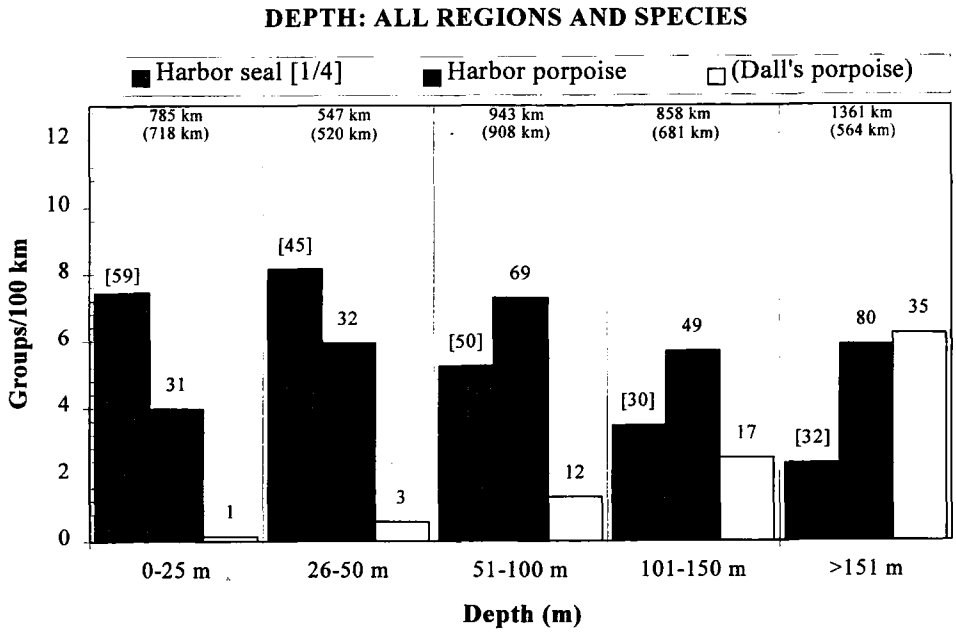

Figure 5. Sighting rate by depth class for harbor seals, harbor porpoise, and Dall's porpoise observed in the study area under acceptable visibility conditions. Seal rates and sightings were four times greater than shown due to data subsampling. Because no Dall's were sighted there, the survey effort for the Strait of Georgia was excluded from the analysis for Dall's porpoise.

Out of a total of 38 geographic cells, 37 contained at least one seal sighting; rates varied greatly from three to 59 groups per 100 km of effort (Figure 4). The highest rates (31–59 groups/km) were found in two clusters of cells encompassing: (1) the northern Gulf Islands, and (2) northeast Orcas Island. The sighting rates adjacent to these cell clusters were also high (21–29 groups/100 km) and comparable to those in the eastern Strait of Juan de Fuca near western Whidbey Island and around Protection and Smith Islands, which are well established haul sites (Huber 1995). The highest rates in the Strait of Georgia (21–29 groups/100 km) were comparable for two cells: (1) between Hornby and Texada Islands, and (2) near the Fraser river mouth and Robert's Bank, an alluvial sand bar that is extensively used for hauling.

Abundance

Density and abundance estimates of harbor seals were not calculated because adequate estimates have already been calculated for this species based on counts of haul-out sites in these waters (see Jeffries et al. 1997; Olesiuk et al. 1980; Olesiuk in press.).

Harbor Porpoise

Sightings and Geographic Distribution

A total of 382 sightings of 549 harbor porpoise were made during the surveys, with 311 of these sightings made on-effort (Figure 6). Group sizes of harbor porpoise ranged from one to three (66% single animals), with the exception of two off-effort sightings of six animals.

Harbor porpoise occurred throughout the study area with few breaks in their geographic distribution. Sighting rates for harbor porpoise were highest in the Canadian Strait and San Juans (8.0–8.1 groups/100 km) and lowest in the Strait of Georgia (1.9 groups/100 km). Sighting rates varied significantly by regions and by the interactive effect of region and depth. When the Strait of Georgia was excluded from the analysis, no significant differences existed between the other four regions. The interactive significance is due to the differences in the depth distribution pattern by region. However, unlike seals, an opposite pattern of increasing sightings with increased depth was apparent in both island regions; no clear pattern was detectable for harbor porpoise in the three other regions alone or all regions combined (Figure 5).

Harbor porpoise sightings occurred in all 19 cells; and rates ranged from one to 21 sightings per 100 km (Figure 6). (The Strait of Georgia was unrepresented for both porpoise species because effort there was mostly less than 40 km per cell). Sighting rates were highest (21 groups/100 km) northwest of Orcas Island and almost as high (15–16 groups/100 km) in the following areas: (1) west of Whidbey Island, (2) off Victoria, British Columbia, and (3) in the central U.S. Strait.

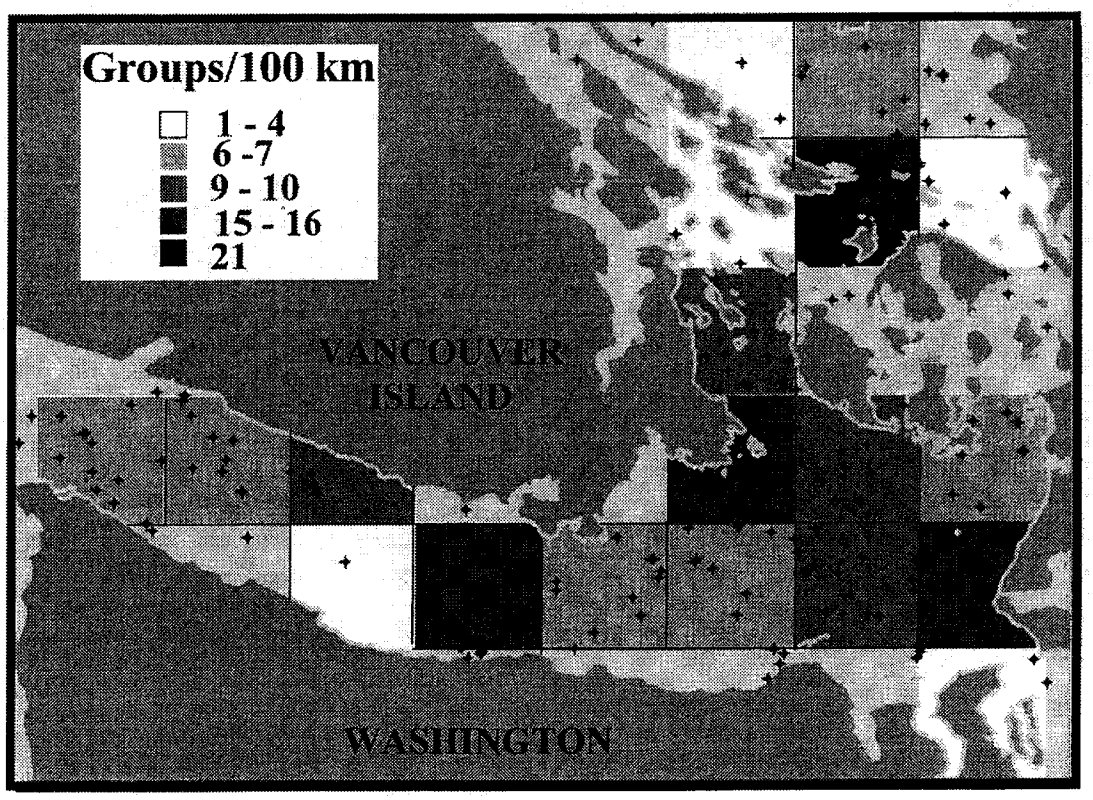

Figure 6. Harbor porpoise sighted while on-effort under acceptable visibility conditions. Effort-corrected sighting rates measured 352 km^2 and contained a minimum of 40 km of aerial effort.

Preliminary Abundance Estimates

Sighting rates showed a steady decrease with distance from the transect line, and a truncation distance of 0.375 km (sightings >64 degrees with 0 = vertical) only eliminated two harbor porpoise sightings. The best model of the sighting distances was the Uniform key with one polynomial adjustment.

The preliminary estimate of harbor porpoise abundance was approximately 6,000, with approximately 50%, 35%, and 15% of the population found in the Strait of Juan de Fuca, San

Juan/Gulf Islands, and the Strait of Georgia, respectively (see Calambokidis et al. 1997 for additional details). This estimate is corrected for the number of animals missed on the transect line (uncorrected estimate x 3.4 = corrected estimate, see Laake et al. 1997). As revealed by the analysis of harbor porpoise sighting rates (Table 1), the density was lowest in the Strait of Georgia. Despite the large size of this region (more than double any other region), it contributed less than 1,000 animals (corrected abundance) to this total. Calculated densities in the other regions were fairly similar and contributions to abundance were generally proportional to their areas.

Dall's Porpoise

Sightings and Geographic Distribution

A total of 97 sightings of 173 Dall's porpoise were made during the surveys, with 76 of these made on-effort (Figure 7). Group sizes of Dall's porpoise ranged form one to five animals, with 87% of the sightings consisting of one or two animals. Dall's were sighted in all regions except the Strait of Georgia.

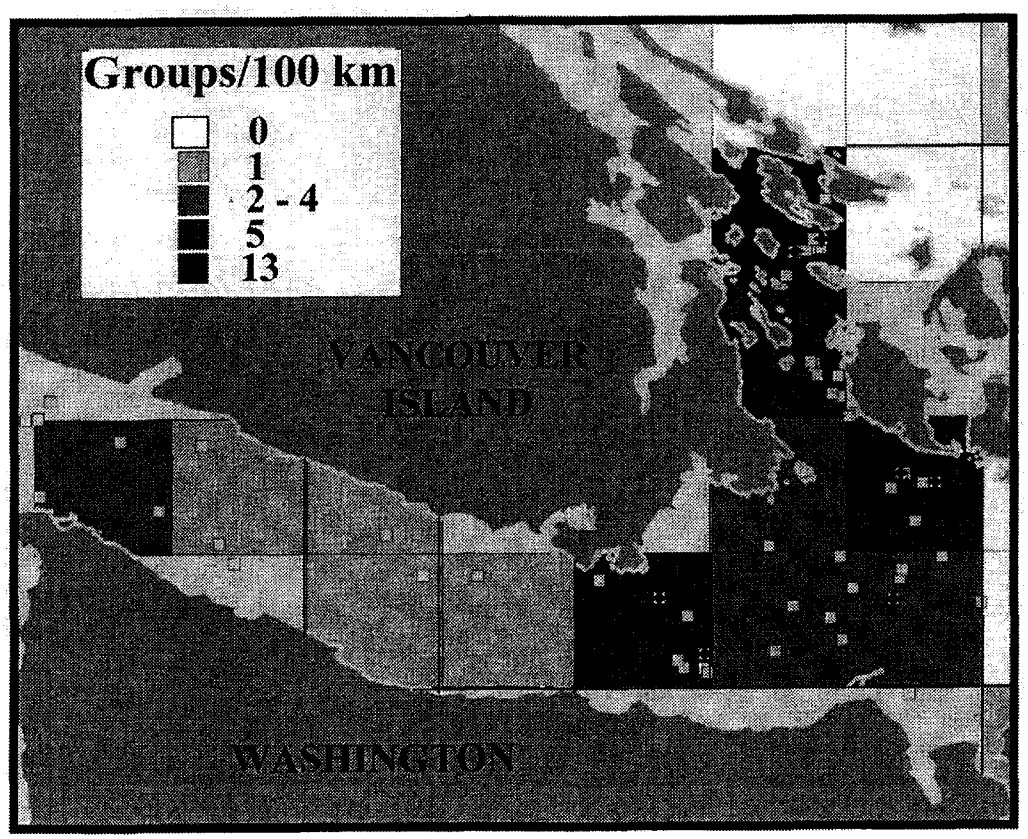

Figure 7. Dall's porpoise and calves (black cross) sighted while on-effort under acceptable visibility conditions. Effort-corrected sighting-rate blocks measured 352 km^2 and contained a minimum of 40 km of aerial effort. No Dall's porpoise were sighted in the Strait of Georgia.

Dall's porpoise were more clumped in their distribution than either harbor seals or harbor porpoise. The overall distribution of group sightings shows few sightings occurring east of Haro Strait and the waters immediately west of Whidbey Island in the eastern Strait of Juan de Fuca. Sighting rates in the regions where Dall's occurred varied little within the Gulf Islands, and were higher (2.2 groups/100 km) than in the Canadian Straits (1.4 groups/100 km). With the Strait of Georgia excluded, (because of the lack of sightings), there were no differences in sighting rate by region. Dall's porpoise were distributed unevenly by

depth, with significantly more sightings in the deepest waters (P<0.001) (Figure 5).

Almost one-third of the geographic cells had zero sighting rates (Figure 7). Dall's porpoise sighting rates in the remaining cells ranged from 1–5 groups/100 km. The exception was for one cell encompassing northern Haro Strait/Boundary Pass and the Canadian Gulf Islands, which was dramatically higher (13 porpoise/100 km). This relatively high rate was the result of 11 Dall's porpoise groups being sighted over several minutes during a single replicate survey.

Preliminary Abundance Estimates

The preliminary uncorrected estimate of abundance of Dall's porpoise for all regions for 1996 was approximately 450 animals, with about 60% and 40% of the population found in the Strait of Juan de Fuca and the San Juan/Gulf Island regions, respectively. No correction factor for animals missed on the transect line is available for Dall's porpoise. Because of the similarity between Dall's and harbor porpoise in body size, group composition, and breath rate, we assume, for this study, that the proportion of Dall's porpoise missed is likely similar to that calculated for harbor porpoise (Laake et al. 1997). With this correction factor, the estimated abundance of Dall's porpoise would be about 1,500 for all four regions combined.

Discussion

Regional Differences

It is suspected that the summer distribution of marine mammals in the study area is affected largely by prey availability, especially for those smaller species with high energetic demands (Morejohn 1979). The trans-boundary waters of the San Juan/ Gulf Island regions, which had the highest sighting rates of all three species with respect to both region and the 352 km^2 cells, are unique from the other waters of the study area in ways that may affect prey abundance and distribution. The channel forming Haro Strait has comparable depths to the western Strait of Juan de Fuca (>300 m), even though it divides the two shallowest regions in the study area (NOAA Nautical Chart). Currents in this area and the adjacent waters around Boundary Passage are relatively strong and can exceed several knots (NOAA Tidal Current Tables 1995). Along with these strong currents are distinct tide rips, zones of mixing which were more consistent and prominent there than the other regions we sampled (SDO, personal observation).

Shore- and vessel-based studies have associated greater concentrations of marine mammals with tide rips (harbor seals: Suryan 1995; Dall's porpoise: Miller 1989; and harbor porpoise: Everitt 1980; Flaherty and Stark 1982; Raum-Suryan 1995). These authors and Read (1983), who observed harbor porpoise foraging on herring at rips near the surface, believe these aggregations of marine mammals are related to greater prey abundance. Herring, an important prey species for these marine mammals (Cowan 1944; Pike and McAskie 1969; Stroud 1981), especially during summer (Everrit et al. 1980; Gearin et al. 1995), are associated with areas of such mixing because of zooplankton concentrations along these convergence zones (Battle et al. 1936). These higher aggregations of prey and the possible action of current upwellings possibly transporting herring closer to the water's surface may lead to increased foraging efficiency (Watson 1976).

The lack of marine mammal sightings in the Strait of Georgia, other than harbor seals and harbor porpoise, was surprising because this region had nearly the highest amount of acceptable aerial effort. The absence of other marine mammal sightings there may be related to either animals temporarily leaving this region or a general avoidance of this region. Because this is the first study to systematically survey these waters, no marine mammal sighting data is available for comparison with other seasons or years. The lack of Dall's porpoise sightings in the Strait of Georgia is consistent, though, with the findings of Cowan (1944) and Pike and McAskie (1969), who reported that Dall's porpoise were uncommon in this region relative to Johnstone Strait to the north (Jefferson 1987) and the waters of the Gulf/San Juan Islands to the

south (Everitt et al. 1980; Calambokidis et al. 1992).

Evaluation of Areas to be Avoided by Fisheries

Although there were significant patterns in the geographic distribution of the three species tested, these patterns may not be dramatic enough to be of great value to management in reducing incidental take levels in gillnet fisheries. Harbor seals and harbor porpoise, the two species incidentally taken most often in the U.S. San Juans, were present in almost all of the geographic cells as well as distance to shore classes. Consequently, significant reductions in takes through regional or habitat closures would be difficult. Instead, these data might better be used by managers for regulating future human activities that potentially could impact marine mammals and habitat quality, especially in those geographic cells where encounter rates were highest.

Abundance Estimates

The surveys in 1996 provide the best estimates of harbor porpoise abundance in the inside waters of Washington and British Columbia due to their greater and better distributed coverage compared to past surveys. This paper also was the first to report abundance estimates of Dall's porpoise for these inside waters. Although the use of the harbor porpoise correction factor (Laake et al. 1997) to correct for the number of Dall's porpoise missed on the aerial trackline is not ideal, it probably provides a reasonable estimate for Dall's porpoise because these two species are similar in body size, travel in small groups, and have fairly short similar dive intervals.

Given the potential risks to harbor porpoise from incidental entanglements and the evidence of their population decline in Puget Sound proper, the preliminary reanalysis of the 1991 survey data (Calambokidis et al. 1992) and comparison with the estimates from this study are encouraging. This comparison indicates that harbor porpoise numbers probably have not declined in the past five years in the U.S./Canadian Strait of Juan de Fuca and the U.S. San Juan Island regions (Calambokidis et al. in press). Multi-year survey data for the other two regions and information on human-caused mortality for all of these inside waters is still needed to adequately assess the effect of these takes on this harbor porpoise population.

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Disease Screening of Harbor Seals (*Phoca vitulina*) from Gertrude Island, Washington

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Introduction

As part of the Puget Sound Ambient Monitoring Program (PSAMP), the Washington Department of Fish and Wildlife (WDFW) has the responsibility for addressing the health and status of marine mammals in Puget Sound. To address this issue, harbor seals were selected as a good indicator species to monitor the overall health of marine mammals. Harbor seals were selected because they are upper-trophic-level predators that are year-round, breeding residents of Puget Sound, as well as being abundant, widely distributed, and relatively easy to study. As upper-trophic-level predators, harbor seals also provide a mechanism for monitoring how contaminants effect the health of various marine species in Puget Sound as well.

As part of PSAMP-related research efforts, WDFW has worked with researchers at the National Marine Mammal Laboratory (NMML) and other agencies to conduct: 1) aerial and ground surveys to determine status and trends of regional harbor seal populations; 2) annual capture and marking of cohorts to monitor vital parameters and reproductive success; 3) blubber biopsies to monitor temporal and spatial trends in contaminants (primarily PCBs); and 4) serologic screening of free-ranging harbor seals for various diseases. Disease screening efforts have been focused at WDFW's primary harbor seal study site at Gertrude Island (near McNeil Island). This site has the largest harbor seal haulout area in southern Puget Sound, with more than 700 seals using this site seasonally.

Determination of the health status of Puget Sound harbor seals has focused on serologic screening for a variety of diseases that have been linked with mass die-offs or illness in seals and other marine mammals from around the world. Serologic screening has been conducted for calicivirus, influenza virus, morbillivirus, leptospirosis, and brucellosis. Tissue samples were also collected and cultured for selected diseases from a number of stranded harbor seals found on Puget Sound beaches.

Methods

Capture and Handling Techniques

WDFW has conducted disease screening as part of ongoing harbor seal research efforts since 1986, with recent research activities authorized under Marine Mammal Protection Act Scientific Research Permit No. 835. The primary method of capturing harbor seals uses a beach seine technique described by Jeffries et al. (1993). Additional seals were captured by grabbing individuals following either boat or beach rushes. Once captured, seals were placed in individual hoop nets to determine weight, age, sex, and marking. Blood for serologic screening was drawn from the extradural intravertebral vein using a vacutainer adapter and an 18 gauge 1.5- to 3.5-inch needle. For blood collection, serum separator and heparinized vacutainer tubes were used. Serum was separated as soon as possible and aliquoted into 1–2 mL samples and frozen (–20 _C) pending disease screening. Heparinized samples were also frozen for bacterial blood cultures.

Collection of Specimen Materials

As part of the Northwest Marine Mammal Stranding Network, WDFW responded to reports of numerous marine mammal strandings from areas around southern Puget Sound. WDFW also has worked in cooperation with NMML to collect samples of marine mammals taken incidental to commercial fisheries. Whenever possible on live stranded marine mammals, a blood sample was drawn for health screening. From dead stranded or incidentally taken animals, blood was also collected in serum separator tubes. Blood samples were spun, serum aliquoted, and frozen. Depending on carcass condition (freshness), a selection of tissue samples was collected. For fresh or slightly decomposed animals, a thorough necropsy usually was performed. Tissue samples for histopathology were collected and stored in 10% formalin. Sections of various tissues were also collected in sterile whirl packs and frozen pending work up.

Assessment of Age Classes

Based on known pupping-season dates at Gertrude Island, and using weight/age correlations for harbor seals from British Columbia (Bigg 1969), ages of individual harbor seals were classified as nursing pup (<2 months), weaner (2–6 months), yearling (6–18 months), subadult (18–48 months), or adult (>48 months).

Diseases and Screening

Calicivirus (San Miguel Sea Lion Virus)

The first calicivirus isolated from marine mammals was San Miguel Sea Lion Virus (SMSV), recovered from two female California sea lions from the San Miguel Island rookery that had recently aborted (Smith and Boyt 1990). Since this first isolation, there have been numerous serotypes of calicivirus isolated from a variety of other marine mammals, including the northern fur seal, Steller sea lion, northern elephant seal, Pacific and Atlantic bottlenose dolphins, and walrus (Smith and Boyt 1990). Serology has shown positive titres in the bowhead whale, gray whale, fin whale, sperm whale, Sei whale, and the Hawaiian monk seal as well (Smith and Boyt 1990). The calicivirus serotype isolated from California sea lions was similar to vesicular exanthema of swine (Smith et al 1973), with clinical symptoms characterized by vesicular lesions (primarily on flippers), abortions, diarrhea, encephalitis, and death. There have been no reported cases of calicivirus in harbor seals.

The serology and virus isolation attempts were done by Oregon State University (OSU), School of Veterinary Medicine, Corvallis, OR. The serum and rectal swabs were tested for evidence of exposure to marine calicivirus serotypes as described in Smith et al. (1978) and Barlough et al. (1987).

Influenza

Influenza virus has been linked to a mass die-off of harbor seals on the New England coast in 1979 and 1980, with acute pneumonia and a secondary mycoplasma bacteria infection were the causative agents (Geraci et al. 1982). Although harbor seals seem to be most susceptible to influenza virus, other species of seals and cetaceans have been reported to be susceptible this virus as well (Webster et al. 1981; Hinshaw et al. 1986; Danner et al. 1998). The influenza virus in marine mammals has been shown to be similar to avian influenza and can be extremely virulent (Webster et al. 1981). Clinical symptoms include outwardly healthy animals that were weak and lethargic, often resulting in death. Although the influenza virus has been linked with mass die-offs of Atlantic harbor seals, it has not been reported in Pacific harbor seals.

Serological testing and attempts of isolation for influenza virus were done at St. Jude Research Hospital, Memphis, TN. Rectal and nasal swabs in culture transport media and serum were shipped overnight. The serum was tested by hemagglutinating-inhibition assay against Seal/Mass/1/80 (H7N7) and Seal/Mass/27/83 (H4N5). The rectal and nasal swabs were transferred to embryonated chicken eggs as well as MDCK cells for culture as described in Webster et al. (1981).

Morbillivirus

Morbillivirus was associated with the 1988 mass die-off of an estimated 20,000 harbor seals and several hundred grey seals in western Europe (Dietz and Harkonen 1989). The causative agent for this disease was found to be a morbillivirus similar to Canine Distemper (CDV) and subsequently named Phocine Distemper (PDV) (Mahy et al. 1988; Osterhaus and Vedder 1988; Osterhaus and Vedder 1989). Since this first reported PDV epizootic affecting seals, other strains of PDV have been identified from other pinniped and cetacean species as well (Duignan et al. 1995a; Duignan et al. 1995b). CDV has also been shown to manifest morbillivirus in marine mammals as well. Since the discovery of these potentially lethal viruses in a variety of marine mammals, screening for PDV and CDV titres has been widespread, not only in the wild but also in captive and rehabilitated animals. The clinical symptoms of CDV- and PDV-infected animals include depression, fever, cutaneous lesions, gastrointestinal dysfunction, nervous disorders, and respiratory distress (Visser et al. 1991; Visser et al. 1993). Morbillivirus has not been reported in Pacific harbor seals.

Serum samples were tested for antibodies to morbilliviruses by the National Institute of Public Health and Environmental Protection (NIPHEP), Netherlands (Dr. A.Osterhaus) in 1986 and 1989; the Department of Pathology, Microbiology and Immunology, University of California, Davis (Dr. D. King) from 1992–1994; the Department of Pathology, University of Guelph (Dr. P. Duignan) in 1993; San Jose State University, Department of Biological Sciences (Dr. J. Boothby) in 1995; and the U.S. Department of Agriculture, Plum Island (Dr. C. House) in 1996. Techniques used by the various researchers included virus-neutralization test to CDV and ELIZA; virus-neutralization tests using PDV, CDV and other morbilliviruses; and by micro titre neutralization test for antibodies to PDV.

Leptospirosis

The first report of leptospirosis in a marine mammal was from a California sea lion in 1970 (Vedros et al. 1971), and this species seems to be most affected by this disease. Epizootics that have occurred within the California sea lion population have been linked to past El Niño events. High numbers of sea lions (primarily 2–8 year old males) are found stranded on beaches with clinical symptoms which may include lethargy, depression, extreme thirst (often drinking from freshwater sources), reluctance to use rear limbs, and renal failure (Dierauf et al. 1985). Leptospirosis has been reported in northern fur seals as well (Dierauf 1990). The causative agent is *Leptospira pomona* or a similar *Leptospira* organism. Leptospirosis is zoonotic, and because of its potential health risk to humans and domestics animals (dogs, cattle, sheep, pigs, and horses), precautions should be taken when handling marine mammals that potentially carry the disease. Leptospirosis has also been linked to reproductive failure, abortions, and multiple hemorrhagic syndrome in fetuses and neonates in California sea lions and northern fur seals (Smith et al. 1974; Smith et al. 1977). Leptospirosis has not been reported from harbor seal populations.

Serological screening for leptospirosis titres was done by Oregon State University (OSU) for samples collected from 1985–1992. Since 1992, leptospirosis screening has been done by the Washington Department of Agriculture (WDA), Microbiology Laboratory in Olympia, WA. At OSU the serum was tested for titres against *Leptospira pomona.* The serum was diluted with .85% NaCl to 1:100, 1:200, 1:400, 1:1800 1:1600 and 1:3200 and tested of antibodies to *L. pomona* antigen using the microscopic agglutination test. Leptospirosis screening done at WDA included testing with *L. pomona, L. hardjo, L. grippotyphosa, L. icterohemorrhagiae* and *L. canicola.*

Brucellosis

Brucellosis is a contagious bacterial disease described in a number of mammalian species, including cattle, bison, swine, sheep, dog, and humans. It is primarily a pathogen of male and female reproductive tracts, characterized by abortion and impaired fertility (Kennedy and Miller 1993). Brucellosis can also infect and cause a variety of clinical diseases in humans (Gelfand et al. 1989).

Infection of marine mammals with brucellosis was first described in 1994 (Ross et al. 1994).

Three different brucellosis strains have been isolated from a number of different marine mammals in the United Kingdom including the common seal, harbor porpoise, common dolphin, Atlantic white-sided dolphin, striped dolphin, hooded seal, gray seal and European otter (Foster et al. 1996). A *Brucella sp.* has also been reported isolated from a Pacific bottlenose dolphin from California (Ewalt et al. 1994). The brucellosis isolates obtained from the marine mammals have been reported as members of the genus *Brucella*, however they do not match any known *Brucella* sp. and probably represent new, undescribed strains (Ewalt et al. 1994). Brucellosis infection could potentially have a major impact on health and reproductive success of infected marine mammal species.

Harbor seal serum was tested at the Washington Department of Agriculture (WDA) Microbiology Laboratory in Olympia for the presence of antibodies to *Brucella abortus* antigens supplied through the National Veterinary Services Laboratory (NVSL) in Ames, IA. Procedures used for testing samples followed standard protocols for *Brucella abortus* testing developed by NVSL. Interpretation of results of screening of exposure to *Brucella abortus* followed standards developed by the U.S. Department of Agriculture. Serum was screened for brucellosis using the Brucella Buffered Plate Agglutination test antigen (BAPA), the Brucellosis Card test (BBA), Rivanol, and complement fixation (CF) test. Supplemental testing was done on a small number of serum samples using Particle Concentration Fluorescence Immunoassay (PCFIA). A seal was considered positive when all tests (BAPA, BBA and Rivanol [>I:50]) were positive; a seal with one or more but not all tests positive was considered suspect.

For culture and isolation of brucellosis from dead harbor seals examined from Puget Sound beaches, tissue samples from lymph nodes, organs, bodily fluids, and parasites were collected in individually labeled, sterile whirl packs and frozen at –20°C. Selected sample were sent overnight on dry ice to NVSL, Ames, IA for bacterial culture and isolation. Samples were cultured for brucellosis by method described by Ewalt (1989).

Representative tissue samples were collected during gross necropsies by WDFW and preserved in 10% formalin. Tissues were submitted to Northwest ZooPath (Dr. M. Garner) for histopathology. Tissues were trimmed, embedded in paraffin, sectioned, and stained. Following histopathology, tissues in paraffin blocks were submitted to NVSL, Ames, IA for brucellosis immunohistochemistries.

Results

Calicivirus

All harbor seal samples from Gertrude Island screened for exposure to calicivirus by Oregon State University were negative (Table 1).

Influenza

All harbor seal samples from Gertrude Island screened for exposure to influenza viruses (Seal/Mass/1/80 (H7N7) and Seal/Mass/27/83 (H4N5)) at St. Jude Childrens Hospital were negative (Table 1).

Morbillivirus

All harbor seal samples from Gertrude Island screened for exposure to morbillivirus (CDV and PDV) at the various laboratories were negative (Table 1).

Table 1. Results of viral disease screening of harbor seals at Gertrude Island by age class.

DISEASE	PUPS	WEANERS	YEARLINGS	SUBADULTS	ADULTS	TOTALS
CALICIVIRUS						
Serology	0/0	0/3	0/12	0/24	0/50	0/89
Culture	0/0	0/3	0/13	0/23	0/54	0/93
INFLUENZA						
Serology	0/0	0/3	0/12	0/24	0/50	0/89
Culture	0/0	0/3	0/13	0/23	0/54	0/93
MORBILLIVIRUS						
Serology	0/0	0/17	0/1	0/34	0/30	0/82

Leptospirosis

Screening of Gertrude Island harbor seals for exposure to leptospirosis occurred from 1986 through 1997, with a total of 81 of 361 harbor seals tested (Table 2) showing low titres (<1:400). All seals tested prior to 1994 (n=93) were negative for exposure to leptospirosis. Of seals tested since 1994 (n=268), 81 (31%) had low leptospirosis titres (<1:400), primarily for *L. grippotyphosa,* indicating possible exposure but no active leptospirosis infection (Table 2). Two additional seals caught in 1997 from other areas had positive titres (>1:400), indicating presence of leptospirosis. One animal was an adult female caught in the Columbia River with titres of 1:800 for *L. pomona.* The other animal was an adult male caught in the Puntledge River near Courtney, British Columbia, with titres of 1:3200 for *L. pomona* as well.

Table 2. Leptospirosis titres in harbor seals sampled at Gertrude Island, 1986–1997

		Negative*		Suspect**		Positive***	
Age Class	n=	Females	Males	Females	Males	Females	Males
PUP	62	18	12	14	18	0	0
WEA NER	64	27	26	5	6	0	0
YEARLING	37	16	15	5	1	0	0
SUBADULT	68	20	38	4	6	0	0
ADULT	130	29	79	7	5	0	0
TOTALS	361	110	170	35	46	0	0

* NEGATIVE = No titres
** SUSPECT = Titres < 1:400
*** POSITIVE = Titres > 1:400

Brucellosis

A total of 263 seals were tested for evidence of exposure to brucellosis at Gertrude Island between 1994 and 1997 (Table 3). A total of 53 (20%) had suspect or positive titres for brucellosis. Twenty-nine (11%) had a suspect titre and 24 (9%) had a positive titre. Additional harbor seals captured in other areas of Washington also showed evidence of brucellosis exposure. Seals screened from haulout sites at Desdomona Sands (in the Columbia River) and Minor Island (in the Strait of Juan de Fuca) resulted in 3/22 (14%) and 14/77 (18%) with suspect or positive titres for brucellosis, respectively.

Table 3. Brucellosis titres in harbor seals sampled at Gertrude Island, 1994–1997.

		Negative*		Suspect**		Positive***	
Age Class	n=	Females	Males	Females	Males	Females	Males
PUP	42	22	16	2	2	0	0
WEANER	77	28	37	5	4	1	0
YEARLING	22	2	9	2	0	4	7
SUBADULT	35	10	10	2	6	3	5
ADULT	87	34	44	0	6	0	3
TOTALS	263	101	109	11	18	8	16

* NEGATIVE = All brucellosis tests negative
** SUSPECT TITRES = One or more but not all brucellosis tests (BAPA, BBA and Rivanol >l:50) positive
*** POSITIVE TITRES = All brucellosis tests (BAPA, BBA and Rivanol>l:50) positive.

For harbor seals screened for titres to brucellosis at Gertrude Island, the age classes that had the highest rates of suspect or positive titres were yearlings (6–18 months old) with 19/29 (65%), followed by subadults (18–48 months old) with 20/50 (40%). The age class with lowest percent of suspect or positive titres were adult animals (> 48 months) with 14/129 (11%). Of all the adult females screened for brucellosis titres in Washington, only one animal was seropositive. This adult female was caught in the Columbia River and showed evidence of having recently aborted based on vaginal distention.

Serum samples were also obtained from an additional 99 harbor seals found dead on Puget Sound beaches and screened for evidence of exposure to brucellosis. A total of 18 (18%) of these animals showed suspect or positive titres for brucellosis. NVSL was able to isolate a *Brucella* sp. organism from four of six (67%) freshly dead animals where serology indicated exposure to brucellosis. The type of brucellosis isolated from Puget Sound harbor seals was biochemically similar to a *Brucella* species identified from a seal in the United Kingdom. However, subsequent DNA testing showed these were genetically distinct strains. The *Brucella* species found in Puget Sound harbor seals was isolated from 27 of 34 tissues and body fluids sampled, with heavy culture growth from samples collected from the lymph nodes, lungs, urinary bladder and feces (Table 4).

Immunohistochemistry techniques found positive brucellosis staining within the uterus and gut of the *Parafilaroides* sp. lungworms from two of the animals where a brucellosis organism was cultured and isolated. In addition to being present inside of the *Parafilaroides*, staining also revealed the presence of brucellosis in inflammatory cells and an abscessed area of the surrounding parachynema (Garner et al. 1997). There was also positive staining in some of the lymph node tissues as well.

Table 4. Tissues cultured for brucellosis from harbor seals stranded in Puget Sound

Tissue Sampled	96-7	96-9	97-4	97-9
Lymph nodes				
Sublingual	x	+		+++
Submandibular			++	
Supra scapular		+	++	+++
Sub scapular	x	+	++	+++
Inguinal	x	ng	++	+++
Mesenteric	x	+	++	+++
Iliac	x	ng	+	++
Renal			+	++
Splenic	x		+	++
Gastric	x		++	+
Mediastinal	x	ng	++++	++
Reproductive			+	++
Hepatic				++
Pulmonary			++++	++
Cardiac				++
Organs				
Tonsil			+	+
Thymus				+
Reproductive tract	ng	ng	++	ng
Liver	ng	+	+	ng
Kidney	ng	ng	++	ng
Spleen	ng	ng	+	++
Pancreas	ng	ng	++	ng

Lung	ng	+++	Pure growth	++
Synovial tissue			+	ng
Eye			+	ng
Feces			+++	ng
Urinary Bladder			++	

++++ Confluent growth (>1000 colonies)
+++- Heavy growth (100–999 colonies)
++ Moderate growth (10–99 colonies)
+ Sparse growth (<10 colonies)
ng No growth

Discussion

Monitoring the status and health of Puget Sound harbor seals has been one of the primary objectives of the WDFW's PSAMP research efforts. Annual health screening for a variety of diseases known to be either zoonotic or to have caused mass die-offs in marine mammals in other areas provides one mechanism to assess health risks to Puget Sound harbor seals. Evidence suggests Puget Sound harbor seals may have been exposed to leptospirosis, although the significance of low-level titres to this disease remains unknown. Regional harbor seal populations show evidence of exposure to a previously unknown strain of brucellosis that may be significant relative to other marine mammals and domestic livestock.

Serology screening indicates that Puget Sound harbor seals represent a generally naive population to diseases such as calicivirus, influenza virus and morbillivirus. The etiology and risks from these diseases relative to Puget Sound harbor seals remains unknown. Research has shown links between seals in areas of relatively high environmental contamination, failed immune response, and disease (Ross et al. 1996), which may also play a role in the health of Puget Sound harbor seals as well. In addition to health risks to Puget Sound harbor seals, the presence of brucellosis in marine mammals harvested by various Native American tribes in the Northwest poses an unknown human health risk related to potenial human exposure and infection. Marine mammal biologists, seal rehabilitators, and fishermen who have direct contact with pinnipeds may also be at risk of brucellosis infection.

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New Tools to Reduce Seabird Bycatch in Puget Sound Salmon Drift Gillnets

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Abstract

We compared seabird entanglement and salmon catch rates in modified gillnets across times of day in the 1996 North Puget Sound non-treaty sockeye fishery. Our objective was to develop fishing gear and techniques that reduce seabird bycatch in salmon drift gillnets without significantly reducing salmon catch. Modified gear incorporated either visual or acoustic alerts (pingers) into traditional nylon monofilament nets. Time-of-day treatments included sunrise, sunset, and daytime fishing. Seabird entanglement and salmon catch rates varied significantly among gear types and time of day categories, but the patterns of variation were species-specific. Results identified three tools to reduce seabird bycatch in Puget Sound salmon drift gillnet fisheries without reducing fishing catch rates: abundance based or ecosystem management, modified gear, and time of day. Fishing 20-mesh visual barrier nets at times of high fish abundance during openings that include either daytime-and-dusk or daylight-only fishing together have the potential to reduce seabird bycatch by up to 70%–75% in years similar to 1996. These three tools were incorporated into management regulations for the non-treaty fishery by the Washington Fish and Wildlife with the endorsement of fishery leaders.

Whale Watching in the Boundary Straits: Growth Trends and Cooperative Self-Management

Richard W. Osborne
The Whale Museum

Abstract

Whale watching in the Boundary Straits of Washington State and British Columbia has grown at an exponential rate over the last decade, and in recent years has accelerated its growth beyond levels of whale watching found anywhere else in the world. Management of this industry has not yet been undertaken through traditional governmental authority, but has been left to non-governmental organizations that have applied intensive educational efforts relying on cooperative self-management.

The retail sale of orca watching in this region began in the late 1970s, but did not gross more than $10,000 annually until 1985. By 1991, ticket sales broke $1 million, and by the end of the 1997 season they approached $5.7 million, with 81 commercial boats from both sides of the border carrying more than 113,000 passengers. Data were collected through questionnaires distributed to commercial operators in 1988, 1991, and 1993, and through empirical observations collected by educational patrol boats that have monitored whale-watching activities since 1993.

Educational patrol boats that promote self-regulation, an industry-based international commercial operators association, and annual public workshops have led to the development of cooperative self-imposed regulations by the majority of private and commercial vessels that engage in whale watching in the boundary waters. Despite uncontrolled growth of the industry, these self-regulatory methods show promise of being effective in sustainably managing the situation.

7C: Birds and Marine Mammals

Questions & Answers

Q: Does this include any of the Washington Coast and Willapa and Grays Harbor?

Nysewander: It did not include the coast. Our particular survey area relates to the Puget Sound Ambient Monitoring Program. It includes everything from the Strait of Juan de Fuca in. That's why I did look at the Columbia River, and we would probably want to check those data out a little more closely. My initial reaction plus my experience having friends that live down there and being down there is that there are not 60 or 70 thousand scoters living in Willapa Bay that would compensate for this type of decline over the years.

Q: Any theories on why you don't see *Brucella* in adults? Do you think they die off?

A: In other mammals, particularly livestock, it appears to be associated with reproductive function. It is bacteria that kind of disappears when reproduction function is not active, so it may be that during the reproductive period we would see it more but it basically disappears and only manifests itself in reproductive cycles. We don't know exactly why it doesn't show up, but it's similar to what's going on with other mammals.

Q: Ed, on the gillnets and bird entanglement, you concluded your talk saying that only 20 percent of the gillnetters (the non-tribal people) were effected and that essentially the tribal fisherman didn't have to follow these new rules to reduce entanglement. How do you think that should be changed or addressed, if it should at all? What are the options for dealing with tribal folks, or is the take of birds, in your opinion, incidental and not unacceptable?

Melvin: Well, just to expound a little bit. The position of the tribes as I understand it, and, of course, I don't represent them, is that it has not been demonstrated to them that there is a conservation issue for common murres or rhinoceros auklets. Therefore, they are not motivated to take action. Secondarily, they don't consider themselves included under the umbrella of the Migratory Bird Treaty Act. However, they do respond to initiatives under the ESA. So, in terms of where things are likely to go in the future, it's difficult to say. Just do you have an idea of the participants involved, in British Columbia, there are about 2,000 permits and in Washington there's about 2,000 permits. In general, the tribal fishers and the Canadian fishers in the last few years have gotten more openings. So, that's where my estimate of about 20 percent of the effort comes for the non-treaty fleet, and it's very approximate. If anything, I think it's lower, actually. So, it seems like if your general interest is to effect seabird conservation through management—and I also need to add this is the first place where there ever has been research to develop tools to reduce seabird bycatch, and put it in place without closing the fishery—we do have the tools. I know the US Fish and Wildlife Service plans to engage the tribes in that discussion and that will be unfolding. Recently because of the inequity of the regulation, it's my understanding that a local court in Skagit County basically issued an injunction that precludes even the non-treaty fishers from having to abide by these regulations right now. From the gillnetters point of view, that is, the non-treaty side, their perspective is that the regulation was essentially unfair. They want to actually apply these tools but they'd like to see them applied uniformly so that they don't wind up losing out.

Q: Steve, when you looked the distribution of the Dall's and the harbor porpoise, did you correlate or take a look at the food fish species?

Osmek: As far as the distribution of the animal relative to forage fish that time of year, we didn't, but that's something that I'd be really interested in. Some people at the marine mammal lab right now, Brett Hanson and Bill Walker, they are looking at diet of both harbor porpoise and Dall's porpoise, so we'll get a better idea what kind of a dietary overlap there might be between the species. And then the next step would be trying to find out what the distribution of the baitfish is. Several years ago I looked through some of the WDFW data, and it's pretty difficult to try to make any sort of assessment of a baitfish at this point. We know where some herring are spawning, of course, and surf smelt, and other species, but to make a broad generalization over that entire study area at this point is pretty difficult to do.

D. Peeler: Mr. Osborne, with the high concentration of boats in Sinclair Inlet this summer, and as I recall there was a Coast Guard boat that was down there most of that time, and I believe your organization also finally dispatched your boat down, what was your view of the compliance with the voluntary guidelines during that period?

Osborne: Well, the 100-yard guideline that the federal government has was not followed at all. We actually had four or five different governmental agencies in there at one point, along with our educational boat, which was actually there first, and they were all giving out different information, so it was not very well organized. But the whales did adapt quite nicely to all that boat traffic. The one day there were 500 boats, they actually got pinned up against shore for about half an hour, but they swam underneath the boats, and then went back to a pattern, and they seemed to be dealing with the boat traffic. But it could've been better coordinated. We were pretty unprepared for something like that.

D. Peeler: I was one of the land-based people looking out over the hoards of boats, and with the movement of the whales, it'd be pretty hard to keep to voluntary guidance. The whales were moving faster than the boats on the day I was there.

Osborne: Yes. Our objective was actually to just have everybody shut off their engines and just sit there and let whales maneuver around. But again, there wasn't a consistent plan as to how to deal with it.

Q: Could you briefly tell us what the voluntary guidelines are?

Osborne: You're not supposed to approach any marine mammal in the water closer than 100 yards, is what it boils down to. That is not based on scientific information. That's mostly based on the fact that most Americans know what the size of a football field is. But the thing to keep in mind is, if you're going to put in a regulation and you don't have any scientific information, you have to do it on some basis. And certainly, this has been in place long enough that we can start to evaluate whether 100 yards is a good distance or not. The industry has taken on additional guidelines. They're eliminating a thing called leap-frogging, which is you drive up ahead of the whales and shut off your engines so that the whales come underneath your boat. They are staying further off-shore so not to block the views of shore-based whale watchers. They have slower approach distances. Under certain conditions, they form lines on the outside. And for us, we're trying to control recreational boaters mostly. And with the commercial whale watchers setting an example it makes it extremely easy for us to show recreational boaters what to do. So really the commercial operators have been critical in this whole management program.

PUGET SOUND RESEARCH '98

WRAP-UP SESSION

Session Chair:

Duane Fagergren
Puget Sound Water Quality Action Team

Wrap-Up Session - Where Do We Go From Here?

Fagergren: I again have the honor of being here: I gave the starting comments and I get to give the closing comments. I think the turn out for this session is a testimony to the dedication of people that are still here.

I hope that the conference has been very worthwhile. I'm very thankful that you all came for whatever length of time you could be here and that some of you are still here.

We will have Jan Newton present the student awards and then we're going to run through a very quick session presenting the interpretation or perspective of different people that have been involved with this conference, and for some of them, many of the research conferences that we've had on Puget Sound. They'll compare this conference to previous conferences; talk about issues that are either in common or new, and discuss a bit about where we go from here.

With that I'll turn it over to Jan and let her give the awards for the student papers.

Newton: I don't think there's much that's more fun than seeing the next wave of good minds come in and recognizing how they're going to bring us into the future. Last night, a friend of mine, actually he works with me, but he's also a friend, Skip Albertson, said a quip, and I think I have it right. He said, 'Freshmen are the ones who come in and bring in new knowledge to an institution and seniors are the ones who leave it there.' I think we've seen, in this meeting, an awful lot of high quality presentations from some students. Some very innovative thoughts. Some very high quality methods of presenting things. Another colleague said, 'Yes, you can tell the student talks because they're the ones you can hear and you can see the good slides and all of that.'

The process in evaluating the student presentations is really difficult because, first of all, there were a lot of them. We had twenty student presentations; ten graduate talks, three undergraduate talks, and seven or eight posters, I'm not sure of the tally there. That's a lot of presentations and as you know there's a lot that goes into scoring a presentation, some of it very subjective. In order to do this we used score sheets that had different categories about clarity, content and presentation, etc. There were numerous anonymous judges in the audience, secretly going around and listening to these talks and looking at these posters and talking with the students and keeping track of them.

I have all of the evaluation sheets that we received from the judges. We're going to give these to the students so each student should get a handful of these evaluations to provide them some information about how their presentation or poster was received. It's a lot more informative than knowing "I won" or "I didn't win." Students will get to see the opinions and the comments of the judges about their talks, the suggestions that were made, and the diversity of opinions that are out there.

Something that we really wrestle with is that sometimes there are no clear winners. People have different opinions and I should say that the judges came from a wide variety of backgrounds. From academia, management, education, etc. I will get down to the really important stuff, but before I do that, I want to thank all of the judges.

We're giving awards in three categories: posters, graduate talks, and undergraduate talks. Each student who wins will get a certificate and a check. I'm going to tell you the winners and the runners up because, as I said, it was really hard to score some of these.

We had seven student posters. The winner of the best student poster is Casimir Rice. It doesn't look like Casimir is here. The runner up is Kyle Ren from the University of Washington and third place is Wendy Simms from the Institute of Ocean Sciences.

We had three undergraduate talks that were very difficult to rank. The winner is Tim Crone. Second place is Lisa Nguyen and the third place is Ken Prentice.

Finally, we come to the category that was the hardest to score. The winner for the best graduate talk is Kelly Curtis. For second place, we had a tie, and it's kind of ironic because they were both speaking on similar topics. Both of them spoke on climate impacts on organisms, and those people are Bill Pinnix and Beth Bornhold. The third place presentation is Brian Haug.

Fagergren: Now, I'd like John Armstrong, being the historian he is, to give his perspective on how we may have plowed new ground or learned new things through this conference or how this compares to what we've seen in the past.

Armstrong: I don't know if I'm comfortable with this historian role, but no one else wanted to do it. I decided what I'd try to do is go over some of the major issues since the mid-1970s. And I thought, well, the way to look at that would be to go back to the past research conferences. The first one I went to was in 1977 called "Use, Study, and Management of Puget Sound" held at the University of Washington. I picked up those proceedings and thought I'd pick out a paper to show how far we've come since 1977. I'd ask you if you'd agree that this paper wouldn't be relevant today because we've gone beyond that: Brian Mar at the University of Washington gave a paper on "Muddling Through the Management of Puget Sound." Probably, he could give that same paper today, 20 years later, although we've tried a lot of things since then.

I thought what might be useful is to really quickly go over some of the major programs, and initiatives, and issues that I've seen over these 20 years. For the folks who've been around that long and longer, maybe it'll remind you of some of the things you've worked on, some of the big issues that came along. For those of you that are newer here, I think you'll be amazed that, even though I'm going to just cover what is a brief list of these things, there's an awful lot that's gone on in Puget Sound as far a science and management in the last 20 years.

The ones I won't mention, because they would come up every year throughout the 20 years, are habitat loss and population growth. Every year we talk about that and every year it seems to get worse.

- When I first started, there were the Metro interim studies, looking at effects of Metro's outfalls on Puget Sound.
- NOAA was starting to fund work in the Strait of Juan de Fuca and the Puget Sound, oil transport related biological studies, the MESA one was looking at various things in Puget Sound, many studies.
- The Boldt decision came, giving the tribes rights to salmon.
- Liver lesions were shown in flatfish around Puget Sound. The whole issue of toxins became bigger and the newspaper printed pictures of hotspots in the urban bays, mainly.
- We start seeing heavy harvest of nonregulated invertebrates and seaweed.
- A decision was made by the Department of Ecology and EPA that all the treatment plants in Puget Sound had to go to secondary treatment.
- There was a big odor problem in West Seattle with rotting seaweed.
- Superfund came along. Commencement Bay became a Superfund site. Now we've got Harbor Island, Sinclair Inlet, Eagle Harbor.
- Some dead whales were found in the Sound; this elevated environmental issues even more.
- The Puget Sound Water Quality Authority was formed.
- Seaweed was looked into, a lot of money went into that, but it never took off.

- Mussel culture was tried. I can't go into a restaurant now without finding Penn Cove mussels somewhere.
- EPA started getting money for Puget Sound with its National Estuary Program and has funded a lot of studies over the years.
- There were South Sound studies back in the mid-1980s, we just heard about some Budd Inlet studies at this conference. There were Budd Inlet studies then, and also studies in the South Sound looking at potential discharge zones.
- Urban bay studies were done in the mid- and late 1980s concentrating on toxins in the urban bays. We had a lot of fishing advisories in those days. I first became aware of those when there was Greenpeace sign on the waterfront in Seattle with my phone number on it as a contact – quite surprising to me – and then King County replaced those a week later because they didn't want to be upstaged by Greenpeace.
- There were lots of Puget Sound reconnaisance studies going around the Sound looking at what were the sediment conditions and the contaminant levels and fish and seaweed and so on.
- Victoria sewage came up and talks about boycotting Victoria. That issue isn't dead yet.
- Mustard gas – there was talk that the U.S. dumped mustard gas at the Strait of Juan de Fuca mouth years ago. No one ever found it though.
- Sea Grant came out with a series of books on Puget Sound.
- Ecology came out with state sediment standards.
- The Puget Sound Ambient Monitoring Program began.
- There was a Puget Sound Conference in Washington, D.C., of all places. Several of us went back to that one.
- There was clam scam: geoducks were illegally harvested. One year we talked about that.
- Herschel taking steelhead at the locks. How many years and how many hundreds of thousands of dollars were spent on that?
- Canadians did some studies, Burrard Inlet studies at Vancouver and Fraser River Estuary studies.
- Harbor seal were shown to be the source of some contaminated shellfish beds in Hood Canal. The way we solved that is we built floats so that the harbor seals would go out and go on the floats instead of on the shore where the clams were.
- The Renton outfall studies; more Metro work.
- Boldt Two came along recognizing the tribes right to shellfish.
- Pacific Marine Environmental Laboratory, an arm of NOAA, stopped doing work in Puget Sound.
- Padilla Bay became a National Estuarine Research Reserve.
- There were studies of the impacts of aquaculture of salmon. Harmful algal blooms then killed a lot of those salmon.
- There was an oil spill in the Strait of Georgia.
- Exotic species in Puget Sound, like *Spartina*, started to be discussed a little bit.
- Juvenile salmon were shown to take up contaminants in rivers.
- The watershed approach became big. This was maybe five years ago. We hear a lot everyday now about the watershed approach.

- We had an agreement between Washington and British Columbia to work on environmental issues and this Puget Sound Georgia Basin Task Force that you heard about at this conference was formed.
- More Budd Inlet studies.
- Atlantic salmon escaped last summer.
- Salmon wars with Canada.
- Exotic species really becoming a big issue now.
- Depressed stocks. We've talked about this over the years. Not many are getting better.
- Marine protected areas are getting popular. Several people mentioned those at this conference.
- PRISM, the UW is starting to try to do more of a concerted, coordinated effort in Puget Sound.
- Endangered Species Act.
- Fish and Wildlife Department – we get the exotic species act and chinook salmon issues and the Department of Fish and Wildlife's funding starts going down.
- Lately, Sea Grant, which published books a long time ago, came out with a CD-ROM on Puget Sound.

This list could go on and on and on. It's just amazing to me when I start thinking back how many issues and projects all of us here and others worked on in the Sound. I guess my conclusion is simple. It's that it's an interesting and rewarding thing to work on understanding and protecting Puget Sound. It's also always going to be a full time job. That's my quick history of the last 20 years.

Fagergren: Curt Ebbesmeyer, would you give your perspective, and then maybe Jan following you, and then Shari.

Ebbesmeyer: Thanks, Duane. I've been around a little longer than John. I remember the days when the Office of Naval Research was the main funder of Puget Sound oceanography, and that was in the 1960s. If you weren't on the Navy funding, you didn't have much to do. That carried through to the mid 1960s, and then West Point kicked in and we got the sewage out of Lake Washington.

What impresses me most about this particular conference is the sheer volume of money being spent on oceanography. It's just enormous. You have a really intensive, first-rate program in the Duwamish. We're not using simple models anymore. The Duwamish Project that Randy Shuman is running is sucking up a significant amount of Boeing Cray time; that's pretty impressive. In Budd Inlet, we're using a similar kind of model, but we haven't tapped into Boeing yet. But the models are being applied are state-of-the-art, Cray level type models, not just in one or two places, but around the Sound. Budd Inlet is a couple of million dollars of oceanography. The UW PRISM effort is a few million spent over a number of years. The Denny Way CSO Program was half a million in oceanography. The Elliott Bay Restoration Program was a half a million. The Hylebos investigation is going on now. There's probably a million or so. If you add up all the pieces, there's several million every year going to understand the oceanography, and I'm just looking at the physical aspects.

Where do we go from here? I still maintain that Puget Sound is dying the death of a thousand cuts. There's no way of looking at what is really happening, overall, to the Sound. I still think it's like the client on the operating table and we're all a bunch of surgeons. We run and we make our little cut and we go out and nobody's coordinating all these surgeons. I think the patient is kind of sitting there and not doing too well, and we're all kind of, maybe, happy, and we all leave the room and the client dies. I don't think that's very good service. I'm still looking for a way to manage overall Puget Sound so we have all this coordinated so that when somebody does something in one

little bay, we know what its overall impact is going to be. I'm very optimistic. We're just lacking that overall coordination tool.

Newton: What Duane asked for is several people's perspectives on what they really learned from this conference. What are your take-home impressions or lessons? So I thought up two, and since I have two minutes, I'll take a minute each. One has to do less with science than it does with the way we're doing science. Similar to what Curt just said, I think one thing that impresses me and actually gives me a lot of hope for the future is seeing some programs coming together and working together. I see PRISM excited to work with PSAMP. I see Canadians excited to work with the U.S., and maybe we're not where we really need to be, but I think we're making a lot of progress that perhaps we weren't making as much before.

I guess I'm a bit more encouraged than Curt in that I do see some larger regional scale studies starting to happen. Department of Ecology is making a commitment, at least in the planning stages, of looking at nutrients in all of south Puget Sound. The program with Metro King County that Randy is heading up is looking at siting wastewater treatment plants and they're looking at central Puget Sound as a whole. I think that we really need to keep going in this direction because I agree with Curt that we could let the system die the death from a thousand cuts. So that's my first observation, and it's quite an optimistic one that we can start to make some progress, though, as we know, it's not easy and it's not cheap either.

The second thing is a scientific observation. I think one thing that I'm exited to see is people looking at the system and looking at it as a system as a whole in the sense of, you saw a lot of talks that were looking at climate impacts on biological systems. I think, all too often, we were looking at our little parcel of water, our little beach, and we weren't really taking into account the fact of interannual climate impacts. I'll mention the two student talks, Bill Pinnix' and Beth Bornhold's on how interdecadal climate variations are changing some biological stocks. I think those are the things we really need to keep tabs on. The impacts of El Nino, a subject near and dear to my heart. Those kinds of things are important so that we can be able to separate out what's coming from humans and what's coming from the natural system itself. Thank you.

Schaftlein: Hi, my name is Shari Schaftlein. I work for the Washington Department of Transportation and manage our environmental initiatives and water quality program. As a DOT employee, I want to thank you for staying this late and let you now that you are all going to be stuck in congestion. But I'd be happy to give you a free coupon to drive your SOV in the HOV, so you can see me afterwards about that.

I'm supposed to represent the typical manager and kind of give you a response on how I would apply what I heard over the past couple of days. In our department we probably spend about a million dollars a week on mitigation and analysis with about a hundred million dollar budget over a biennium. We've got about $1.5 billion of construction going on over a biennium. About 30 EIS's at any one point in time. A couple hundred projects and 20 year long range planning going on. So, I need your data, I need it now, and I need it to help affect decisions and moneys that are being spent.

I want to share with you some perspectives of trying to be a translator between the science and the policy makers, particularly in a large department like DOT, which would be reflective of many public works or large development folks. You deal with some issues such as your manager saying, 'I watched a show about fish in Alaska last week, their fish seem to be able to jump really high. Why do we have to fix our fish passage problem in Washington State? Can't our fish just jump higher like the one in Alaska?' And you start seeing the interdisciplinary gap between environmental science and civil engineering. To take it a step further in terms of analysis, I've worked on a value engineering team with a geotechnical engineer who complained to me as an environmental scientist, 'You know,

you all aren't very credible. Your science keeps changing. You keep changing what you're evaluating. You don't know whether what you do works, etc., etc. I had to defend my profession and remind him about how long we have been building roads and building bridges. Since Roman times, before Roman times? How big of a budget does the U.S. government put into analyzing every conceivable thing you'd want to know about asphalt and concrete? And the budget just soars compared to what federal highway officials spend on environmental research. And I reminded him that our science was only about 20 years old and that there are incredible variables to deal with, and we are working with issues that don't lend themselves to complete mathematical models that are solvable. We can't deal with everything in a lab like you can with geotechnical engineering.

So how have I been listening to the results presented at this conference? I'm listening to hear if the results conclusive. Will I spend money differently? Do the results represent additive information? Are the folks presenting this in a way that tells me, "Here's step one and that will lead to something in the future." Have you ruled out an option for me or narrowed my choices? Is it just pure research? Tell me what it is so I know how to fit it in, in terms of making a management decision?

I'm also reminding folks that we have a very large research budget and call help fill in the gaps of research that needs to be done, if it's done in an applied way.

I certainly wanted to congratulate the folks who presented their presentation in the form of: "here's what I'm going to tell you; here's how you will use this data; here's how decisions will be made; here's what my customers thought about the research."

I feel very positive about the results of the conference. We tried to set it up and encouraged the authors to describe next steps and apply it to policy perspectives, and I think we accomplished that and I talked to a number of people who felt that that was a benefit of this conference in describing what their research meant in terms of policy and management decisions. I think the next steps in terms of what we have to look forward to in the future are rolling up the data to support prioritization. There was progress in that. There was progress in large-scale ecosystems analysis. Folks have complained that don't do cumulative impacts analysis at our department. Well, we can't do it if no one else has done it to help affect how we're going to develop our transportation system.

We need cost-benefit data, most importantly. We're trying to figure out how we take limited resources and distribute them to whatever the priority problem is. That's a big debate right now. When I'm advocating for resources in my department, I'm going up against people who say, "Well, we need to do this safety improvement because 14 lives will be saved and X number of products will get to the port quicker, and all that means that six million dollars of benefits will exist for this one million of cost. Shari, how much benefit is there for that fish passage? How much benefit is there for that stormwater retrofit, etc." And I just have to say well, it costs X million and it's really important and people feel good about it. You're kind of limited in competing right now when you try to go up against cost-benefit analysis in a department that's trying to shift to that. I think other departments are having that same kind of experience right now. As we evolve and look at what we include, I think cost-benefit analysis will help us tremendously.

I want to show a graphic now, and ask you all to think about, did the science that you have heard over the past couple days get reflected? The legislature just ended at 10:30 last night and has set in motion a number of policy actions and budgets to try to attempt to deal with what we've been talking about here today. I wanted to highlight the results and share with you some of the moneys and ask you to review this legislation. Think about whether your research results are represented.

When you take your 25-page paper and squeeze it down into an executive summary and squeeze it down in a paragraph and share it with a legislator and see it end up in a bill, you might be appalled. And you might be appalled when you take your research and cram it into something and give it to your policy wonk and have them explain it to the legislature and see what kind of questions get asked, you might get appalled. Science does somewhat get lost in our public policy debates.

With House bill 2514, we have a watershed-management-planning bill in this state right now. Did the science get reflected? I think, definitely. There was much debate over just having a water quantity bill, and many people worked very hard to try to get the option, at least, to include water quality and habitat in that bill. So, we're making progress with that concept. And I think there's about five million dollars going into that to go out to locals and 14 staff at Ecology to provide technical assistance.

Wetland mitigation. It was certainly recognized by the legislature that we've got to move mitigation banking, and they put some language together to try to move that forward in a consistent way around the state, and the legislature is backing that and expecting reports on how well we are doing to get that implemented.

Advanced mitigation. The legislature put in two million dollars in our account for us to start doing mitigation in advance of a project. So, for example, if we add a lane to I-5 down to Portland, and in the Chehalis basin we might create a wetland bank now, years in advance of that project happening, a big huge bank for all the little bitty impacts we're going to have. That would make ecological sense. We've got the moneys to do that and some authorities to do that now. And the legislature has promised about another 20 million dollars to support this over the next six years.

On fish enhancement and permit streamlining, the legislature put in over five million dollars to fix fish passage on non state roads and an additional half million dollars on state roads and looked at permit streamlining. How do we get these projects on the ground quicker?

Finally, the salmon recovery-planning bill passed as well. And a lot of science evolved into that discussion as well. There was a science advisory team included in that, which should be one of the bullet points there listed. To have an independent science, to make sure we're covering salmon in a scientifically legitimate way.

I think put in a little over 20 million dollars to go to on the ground projects for restoration. So all the work that we heard today on projects, there's money there to start doing it in a prioritized manner.

It was kind of comical to hear the legislature talk about critical path thinking. They could come up with some of these science concepts and see it to the end.

So I think there was tremendous progress, and a lot of things that we were talking about made it into these bills, and I would ask the scientists and folks in this room to recognize that all these bills, and many others that we couldn't list here, have technical advisory committees and what-not, where we need to get the science working with the policy and get it implemented. And certainly, as Jan mentioned, this is requiring a lot of interdisciplinary work when we start doing tradeoff analysis and prioritizing within a watershed.

Fagergren: Bill Pinnix, would you mind stepping to the mike and giving your perspective, and Tom Putnam, if you would follow him and give a minute or two, I'd appreciate it.

Pinnix: Duane asked me to give my feelings, as a student, on this conference. After the panel, I'm not sure what I have to say other than what I saw here was a big step forward (at least in my mind, having not been to a Puget Sound Research Conference before), but a step forward in interdisciplinary research, or conferences that bring people from very different scales of the scientific community: from management to biology to large scale systems into the same conference to speak about a shared resource.

I've been very privileged to work in an interdisciplinary research group at the University of Washington looking at the effects of climate impacts on the Pacific Northwest. The research that I do concerning salmon, I could not do alone. I couldn't do as a fisheries biologist. I'd still be doing histology of salmon ovaries, had I not been in this group. I've learned an immense amount of

knowledge that is stored in other aspects of science.

And not only de we learn what other scientists are learning, but we learn new methods of analyzing old data. A lot of what I do is take data that has been collected for the last 30 to 40 years and re-analyze them with new techniques, and lo and behold, patterns emerge that people have not been able to see before. So I think that this type of forum is extremely useful for educating, not only scientists and managers, but that we can take this education to the community and help educate others.

My only suggestion is that these happen more often than every two or three years. I'd like to see these happen every six months. I'm sure not a lot of research can be done that fast, but there's a lot more out there. Thank you.

Putnam: I'm Tom Putnam. I'm on the Puget Sound Council, which has turned out to be kind of a nexus point for trying to implement some of the decisions and the things that are going on in science. This is the fourth Puget Sound reserach conference I've been to.

I've noticed the fulfillment of a lot of the original ideas that were talked about back in the early 1980's. We were talking then about what would it be like to talk about a watershed. What's a watershed? What's an ecosystem? What would it be like to manage based on these concepts? For me it's really exciting in the last couple of days to see studies that reflect these concepts. We're now getting data based on research based on these concepts which may seem pretty basic, and it may seem we're not as far along as we should be, but it's a lot of progress in the last 12 or 14 years.

The lack of data, for a lot of things, has been an excuse not to act. We don't know if fish stocks are really crashing, We don't know what's going on. That's been an excuse not to act. Now, we're getting data. We're getting the basis to go ahead and act which I think I'm also seeing a little more confidence on the part of scientists and people doing these studies and a little more willingness to participate and to suggest and say, 'This is what we ought to do.' I think science is traditionally more reserved, has been more reserved. I'm really encouraged to see people coming forward and working on these issues and doing that.

I'm also very impressed by technological refinements. I make films for a living, among other things, and I made a film about Puget Sound in 1990, and I was trying to visualize a lot of the stuff that was going on then about dynamic models and layering of GIS data and integrating things; the PSAMP data, and things like that. It's really exciting to see PRISM and some of the other ways that we're beginning to visualize. I think that is one of the most important things, and that's where we go from here. We go out from our circle of science and policy and offices, and we go out to the public with this and we let them understand what is at stake and the dynamics, and we get them out there in nature and on the water and see the fish and the birds and what an incredible place we live in. Thanks.

Fagergren: Thanks, Tom. Jacques White from People for Puget Sound. Would you like to say few words?

White: First of all I'd like to thank the Puget Sound Water Quality Action Team and the Advisory Committee for putting together a really good conference. I'd like to give the unofficial energizer award to Jan Newton for participating, I think, directly in at least five sessions, either as a panelist, a speaker, or a moderator. I think that you all should pat yourselves on the back a little bit.

This is my first Puget Sound Research Conference. I came here from the Chesapeake Bay Region where I was a research scientist, and they put together a similar meeting like this, and I don't think it was any bit better in terms of quality, in terms of quantity of material, in terms of the creativity that I'm seeing, and in terms of direct addressing of some serious problems that they have.

They do the kind of work that they do there, at least from their funding from the EPA, on about 20 to 40 times as much as the money that you guys get, and you're doing quite a bit of good work. If I've ever heard a reason or a justification for getting more resources here to continue the good work you're doing, I think that that is an indication of it. With that said, I think I have a couple of comments that will echo some of the comments that were made by the earlier speakers.

I definitely agree with some of the things that Shari said. I think there are some challenges that are before us. Everything that I see right now through my work for People for Puget Sound and habitat restoration is kind of focus through salmon goggles, and that focus is intensifying. So the things that I say are going to be related to that.

At the conference, I heard that the National Marine Fisheries Service and EPA are going to work together to unify requirements for ESA and the Clean Water Act to streamline the need for permits for users. I would like to compare that statement to evidence that was not presented here, but that the EPA is lowering cleanup requirements for PCBs in Commencement Bay, on the one hand, and on the other hand, NOAA scientists at the meeting today presented information that there's significant contamination of salmon and other resources in Commencement Bay systems. So what I learned is that National Marine Fisheries Service and EPA coordination to protect fish and water quality has not yet happened, and my message to you all is, 'Please help, if you can.' If you can figure out a way to make that move that forward that would be a really good thing.

The other issue echoes directly some of the things that Shari said. What I didn't learn is how to carry out a limiting factors analysis for salmon in an entire watershed that will allow us to prioritize restoration projects and make realistic estimates of current and projected system carrying capacity. Notice that I didn't say, result in more fish. There are other factors besides habitat – climate conditions, harvest, and hatcheries – that also impact fish. But we don't have a good idea of how to directly go from a restoration project or a number of restoration projects to a number of increased carrying capacity for our watersheds. As we think about spending millions and millions and millions of dollars on restoration, that that's something that we need to do. So I would suggest that we get to work on developing a methodology to do cost-benefit analysis that indicate, not only the economic cost effectiveness of a given restoration action, but also maximizes benefits to total ecosystem services to fish and other natural resources for a given project. I realize I'm not asking for much, but those are my comments. Thank you very much.

Fagergren: Tim Ransom, do you have a statement to make?

Ransom: Just a couple of comments. The first being that if Mr. Pinnix wants to see this every six months, he should come talk to Dave Sale and then me about what it takes to do this. I want to point out that Dave and his crew, Joanie Pop, Scott Redman, Jan, did all this for us, and having done it twice myself, I do have a certain perspective to that.

I have a comment on the quality of graphics on the screen, but I'm not going to go into that right now because I'm too tired. I'll simply point out that the best graphics I saw, and the best talks, in terms of technique, that I heard, were given by students, and I think that's a wonderful sign.

Secondly, just as an overview, I remember in 1991, I believe it was, the first conference, there were a lot of talks about individual species, and we all came away from that conference saying, we've got to think systems. And that's what everybody went and did for the next four or five years and we got into the watershed process. And that worked for a while and it developed other kinds of larger system processes. We're now back to thinking species in the future. We can now be talking about fish and I challenge us to think about how that is going to drive us for the next three years until the year 2001 when we're going to be here again, or somewhere like it, asking ourselves these same

questions. Thanks.

Fagergren: It's my understanding that Kelly Curtis, who is the graduate award winner, is now here and so is Beth Bornhold, who was second in a tie with Bill.. Could you please stand and be recognized. And Kelly, we have the award here if you'd like to come get it after we're finished. I would really appreciate if someone, whether it's Beth, or someone else from our good friends from Canada come forward and say something from their perspective coming down here. We really try to bill this as a Puget Sound/Strait of Georgia Conference. We really appreciate the many very good papers presented by Canadian researchers. I'd really appreciate it if someone would come forward and say something.

Bornhold: I was kind of hoping I wasn't going to be noticed, but I guess somebody saw me sitting there. I was really excited to come up here and to hear what was being done in Puget Sound. I knew a little bit about what was being done in Strait of Georgia from my own work, but it was really good to hear all the similar work that's being done in Puget Sound, and to hear how the future looks towards the Canadians and the Americans working together, because I think we are doing a lot of similar work. The two basins aren't separated. I mean there is an international border there, but the water doesn't see that, so I think it's really important to continue to look across that border and to work together. And that's really what I got out of the conference was seeing that, so hopefully we'll continue to do that.

Fagergren: Thank you very much, Beth. Tim, I appreciate you thanking Dave. I wanted to have the last word to thank Dave for all the hard work he's done, and Joanie Pop from Event Dynamics. Dave, if you want to say something, I think you have earned the right to say the last thing and then I think the conference is over. It's 5:00 and we wanted to get you out of here at 5:00.

Sale: Well I'll talk really briefly. As has been talked about at previous conferences, we discussed a wrap up session. In the past it's always been set aside because we've felt "Who's going to want to come to a session at 4:00 on a Friday afternoon? Everybody's going to want to go home.' We thought that we might get 20 or 30 people here. I think it says a lot about everyone here in this room, how many people are here. I think you owe yourselves a round of applause for sticking around.

One of the things that was really exciting for me about doing this was start with the individual abstracts as they came in and see all the pieces of work that are being done and to see them come together as connections among them become clear. Sometimes that gets lost in talking about individual work.

One of the things we tried to bring across at this conference is that there are a lot of efforts going on right now to integrate our work: PSAMP or PRISM, the Georgia Basin Initiative, the Task Force across the border. I think that we really need to keep that sort of thing up. There's a lot of complexity to both the environmental and cultural systems around here, but it doesn't mean that we can't get at the problem. Thanks a lot for coming.

PUGET SOUND RESEARCH '98

APPENDICES

Poster Session Abstracts

Author Contacts

APPENDIX 1: POSTER SESSION ABSTRACTS

Response of the P450 RGS Assay to Extracts of Sediments Collected From Puget Sound, WA

Jack W. Anderson and Jennifer M. Jones
Columbia Analytical Services

Edward Long and Jawed Hameedi
National Oceanic and Atmospheric Administration

The induction of the cytochrome P450 gene family, specifically CYP1A1, in response to toxic and/or carcinogenic organic compounds is widely used as a biomarker for exposure to contaminants in the aquatic environment. Organic compounds, including dioxins, furans, coplanar PCBs, and high molecular weight PAHs, are known to bind to an intracellular cytosolic protein referred to as the aryl hydrocarbon (Ah) receptor. This complex is translocated to the nucleus of the cell, where it interacts with xenobiotic response elements in the promoter of the CYP1A1 gene and causes transcription of the P450 enzyme system. CYP1A1 induction has been used in the development of toxic equivalency factors (TEFs) for polychlorinated dibenzo-dioxins (PCDDs), polychlorinated dibenzo-furans (PCDFs), and PCB congeners as a measure of their potency relative to 2,3,7,8-tetrachlorodibenzo-p-dioxin (Safe 1994). Similarly, TEFs have been developed for PAHs as a measure of carcinogenic potential compared to B[a]P (U.S. EPA 1993).

The P450 Reporter Gene System (RGS) measures induction of the CYP1A1 protein via the reporter gene, firefly luciferase, to determine the presence of inducing compounds in environmental samples. As such, RGS gives an actual assessment of the potential of contaminants on sediments at a specific site to produce chronic and/or carcinogenic effects of flatfish if they were to occupy the site. It also gives an indication of the chronic effects on benthic organisms at the site, as an RGS response above 60 g of benzo[a]pyrene equivalents per g was highly correlated with degradation of infaunal communities. This testing program was designed to determine the potential toxicity and carcinogenicity of sediments collected from Puget Sound, Washington. The results of this project illustrate the ability of P450 RGS to identify, rapidly and inexpensively, the most toxic and hazardous samples within a harbor, bay, or coastal section. Using the entire data set (n = 100), 11 sediment samples were identified as containing concentrations significantly greater than the mean B[a]PEq, using the 99% confidence interval. When Everett Harbor is considered a point source of contamination within the Sound, 15 samples from that area were excluded and an additional statistical analysis of this data set (n = 85) identified 21 samples as significantly greater than the mean. A strong correlation (r2 = 0.91) between the RGS B[a]PEq and the distance from a station in Inner Everett Harbor was observed.

The Widespread Occurrence of Elevated Summer Stream Temperatures in Upper Hood Canal Watersheds and Relation to Riparian Land Uses

Peter Bahls
Port Gamble S'Klallam Tribe

The objectives of this study was to assess summer stream temperatures in upper Hood Canal watersheds in relation to state water quality standards and associated riparian land uses. Twenty nine max/min thermometers, placed in 20 streams, were checked weekly during the summers of 1992, 1993, and 1994. Based on preliminary findings, more intensive sampling on three streams was

conducted in 1995 and 1996 using continuous reading thermometers. Results show that 14 of the 29 stations sampled between 1992 and 1994 were in violation of state water quality standards. An analysis of stream temperature in relation to riparian condition indicated that loss of forested riparian zones through agricultural use was the primary cause of elevated temperatures.

Real-time Monitoring of Bluff Stability at Woodway, Washington

Rex L. Baum, Edwin L. Harp, Richard G. Lahusen, William J. Likos, and Philip S. Powers
U.S. Geological Survey

Damaging landslides occur almost every year on steep bluffs near Puget Sound. Most occur during or after periods of heavy rainfall. Previous workers have attributed such slides, particularly the deep ones, to groundwater seepage within the bluffs. Few actual measurements have been made, however, to study the relationships between rainfall, seepage, and bluff stability. During the summer of 1997, the U.S. Geological Survey began a project to monitor rainfall, groundwater pressures, and slope movement at an unstable bluff adjacent to the head of a slide that derailed a freight train during January 1997. The site is in Woodway, Washington, about 10 km north of Seattle. The monitoring project will help clarify the time lag between rainfall events and resultant water-pressure changes, the magnitude of seasonal and short-term water-pressure variations, and the effects of water pressure changes on bluff stability. Field data are collected every 15 minutes and relayed by phone to a computer network where they are processed and then presented on the World Wide Web. Near-real-time monitoring of the site will also allow us to test and refine technology that might be used for landslide forecasting, emergency notification, or mitigation.

Puget Sound Intertidal Habitat Inventory: Shoreline Characteristics Mapping

Betty E. Bookheim and Helen Berry
Washington Department of Natural Resources

Accurate information on the quality, quantity, and distribution of intertidal habitats is important to monitoring and sustaining the health of Puget Sound. As part of the Puget Sound Ambient Monitoring Program (PSAMP), the Nearshore Habitat Program (NHP) in the Aquatic Resources Division of the Washington State Department of Natural Resources (DNR) inventories intertidal habitats in Puget Sound.

Intertidal habitats are characterized by interacting physical, chemical, and biological factors. The data collected by NHP focuses on two components of intertidal habitat: vegetation types and shoreline characteristics. This poster summarizes information and methods used to survey the shoreline characteristics component of our inventory. The physical attributes described in this method are derived from "A Marine and Estuarine Habitat Classification System for Washington State" (Dethier, 1990) and includes information on system, subsystem, wave or current energy, substrate, and water regime. The mapping methods used ground data in conjunction with photo-interpretation of color infrared aerial photos.

Final delineations were completed on 1:12,000 scale DNR orthophoto maps using a Zoom Transfer Scope and then digitized.

Inventory results are available in digital GIS format or paper maps. This information is being used in conjunction with our DNR intertidal vegetation inventory layer and other habitat information for management, land-use planning, and research.

The Regional Geologic Framework of Puget Sound, and its Application to Geologic Hazards

Derek B. Booth and David R. Montgomery
University of Washington

Kathy Goetz Troost
Shannon & Wilson, Inc., and University of Washington

Understanding of the geologic framework of the Puget Lowland has been hampered by intrinsically complex stratigraphic relationships, obscured by dense vegetation, and confounded by outdated human comprehension of Quaternary history. These problems are nowhere better expressed than in the Seattle-Tacoma area, where the distribution and sequence of glacial and nonglacial deposits have been debated by geologists for decades. We are particularly interested in the application of geologic mapping to determining the continuity of aquitards, revealing the structural deformation that expresses the region's active tectonism, and predicting geologic hazards associated with slope instability. While developing a basic geologic framework, we are also utilizing radiocarbon dating, paleomagnetic studies, and tephrochronology to determine the distribution of, and to establish a regionally based chronology for, the deformation of critical Quaternary deposits. We are working most closely with the U. S. Geological Survey, but because of a long history of public and private geologic studies in this area we are emphasizing a broadly collaborative effort. When integrated with geophysical models of the Earth's crust beneath Puget Sound, this geologic framework can validate predictions of large-scale tectonic deformation expressed by the region's high seismicity. When added to a simple slope-area model that already can credibly predict the location of many observed landslides, this framework should permit a much better understanding and anticipation of catastrophic hill-slope failures.

Identification and Delineation of Deposits from Log Handling and Pulping Operations Using Sediment Profile Imaging

David G. Browning and Gene Revelas
Striplin Environmental Associates

Organic particulate deposits associated with log handling, log storage, and pulp-mill discharges in marine and fresh waters have recently come under increased regulatory scrutiny. A first order evaluation is determining the horizontal and vertical extent of these deposits. A method has been developed whereby wood debris/fiber volume estimations are made by comparing the amount of wood and fiber particles in sediment profile images (SPI) images to petrographic modal estimators. Volumetric estimates can be determined for the top 10 cm of the sediment column or the entire depth of the sediment column represented in the SPI image. Where optical contrast between wood debris and the sediment column is high, particles as small as 0.5 cm can be identified. This technique has been used to delineate and estimate the percentages of debris in the sediment column associated with log rafting and storage in Commencement Bay and Lake Washington, WA in addition to characterizing a pulp effluent deposit in a southeast Alaska fjord. In each study area, differences in wood/pulp debris morphology and sedimentary fabric were observed. Areas containing the greatest amounts of wood debris exhibited the shallowest apparent redox potential discontinuity (RPD) depths in each study. Shallow RPD depths, coupled with highly reduced underlying sediments, are indicative of organic loading and high sediment oxygen demand. RPDs generally deepened away from the areas containing discernible wood/pulp debris. The identification and estimation of amounts of wood debris using SPI provides a primary measure of wood debris/pulp

deposit extent, whereas the distribution of the RPD depths provide a secondary measure of the degree of sediment organic loading where distinct wood particles can no longer be seen.

Monitoring Non-Point Source Pollution in an Agricultural Watershed: Water Quality in an Estuarine Slough, Padilla Bay, Washington

Douglas A. Bulthuis and Robin M. Cottrell
Padilla Bay National Estuarine Research Reserve

Padilla Bay National Estuarine Research Reserve monitors water quality in Padilla Bay and its tributaries as part of the National Estuarine Research Reserve System-Wide Monitoring Program. Joe Leary Slough, the largest freshwater tributary to Padilla Bay, drains a predominately agricultural watershed that includes orchards, berries, beef grazing, dairies, and annual crop agriculture. Salinity, temperature, dissolved oxygen, turbidity, and pH were measured at 30-minute intervals for more than one year at the mouth of Joe Leary Slough. The data indicate tidal influence, seasonal differences, storm event responses, and the effects of agricultural practices.

Shellfish Farm on Hood Canal

Colleen A. Burge, Amalia C. Baker, John Pitts and Charles Baker
Quilcene High School

The Quilcene-Brinnon Schools Shellfish Science Club is an educational, high school club that raises oysters and teaches the community about water quality. The oysters are raised on both Quilcene and Dabob bays off the Hood Canal. 4.7 acres of beach were donated by Jefferson County and the Washington Department of Fisheries and Wildlife. The oysters raised are sold at fairs, festivals and an annual community dinner. At these functions, water-quality brochures are handed out to stress the importance of clean water to the community.

Student members have a variety of educational activities for participation, from business procedures to labor intensive work. The club's main goal is to raise enough money to take a fun and educational, aquaculture-related field trip every two years.

Quilcene High School students have managed and operated the model farm for over three years, receiving two environmental awards, one locally and one nationally. The club hopes to continue to raise oysters and teach the community about the importance of water quality.

Application of Regional Tribal Fish Consumption Study Data to Risk Assessments for Local Sites

Christine M. Chew and Nancy A. Musgrove
Roy F. Weston, Inc

Because fish consumption behaviors vary widely among different populations, site-specific exposure data and application of those data are critical to ensure realistic estimates of exposures and resulting potential risks. A recent study of fish consumption habits of two Puget Sound Native American tribes provides substantial information on both the fish harvesting and fish consumption patterns of tribal members. This study provides consumption rates for all fish and for functional groups of finfish and shellfish, as well as information such as preparation methods, harvesting areas, and parts of the fish consumed. Because these data may serve as surrogates for other Puget Sound tribal or subsistence populations, direct application of values reported in the study may not provide

reasonable estimates for the different exposed populations. Site- and population-specific exposure issues must be addressed. For example, types of finfish and shellfish harvested, the harvestable amount of these fish available at the site, and the portion of consumed fish harvested from the site affect how these data can best be applied to risk assessment calculations. Where possible, fractional use of averaged data may provide more accurate surrogate values than unmodified data. In addition, further examination of the data used in the fish consumption study has yielded a more specific breakdown of exposure patterns with particular regard to different types of shellfish.

An Indicator Study of the Environmental Health of the Sequalitchew Creek Watershed

Emily E. Cudney, Jessica J. Fox, Kris M. Grinnell, Ryan W. Smedes, and Kirsten C. Workman
Pacific Lutheran University

Sequalitchew Creek flows three miles from Sequalitchew Lake on Fort Lewis, through the City of DuPont, into the southern portion of Puget Sound. The watershed is small, but on the verge of rapid development as a planned community that includes residential, commercial, and industrial land use. The community wants to maintain a small community feeling and a healthy creek system as this development occurs.

As part of a class on Environmental Methods of Investigation at Pacific Lutheran University, we collected geological, chemical and biological field data from the stream as well as assembling land use, economic, demographic, and political data about the entire watershed. We used these data to develop a preliminary indicator study of the environmental health of the Sequalitchew Creek watershed. We identified key issues that the watershed faces and selected indicators to be monitored over time. These indicators include measures of the creek's properties: discharge, total phosphate, and fecal coliform. These indicators also include as characteristics of the watershed: percent of residents who work in DuPont, types of businesses, road sizes, and acres of open space. For each we identified an optimum value and made specific recommendations to help the community improve the environmental health of the watershed.

Flow Estimation Model for Small to Medium-Sized Streams in Puget Sound Based on Sparse Measurements and Precipitation Data

Matthew Davis and Chris Cleveland
Brown and Caldwell

Flow histories of surface-water discharge are an essential piece of information in many studies; however, dedicated flow monitoring can be expensive and difficult to maintain. Hydrologic models have been used with success to estimate flows when measurements are not readily available. Some models however are data intensive, requiring information on soil types and properties. Quantification of these parameters can be expensive and time consuming. A model has been developed to predict stream flows using easily attained measurements: daily precipitation data and intermittent stream flow measurements. The model routes precipitation through a series of "boxes" that idealize different storage and transfer processes within a watershed. Model calibration adjusts the parameters that control flux into and out of the boxes. Intermittent streamflow measurements are used to guide the calibration process and evaluate error. Optimization of the model parameters may be accomplished through trial and error or automated with an optimization technique such as a genetic algorithm. The model is simple enough to be used in a

spreadsheet or may be coded in a more robust form in a -alone application. The model is well suited for streams draining small to medium-sized watersheds and was applied successfully in the Budd Inlet Intensive Study to nine streams.

Nutrient Transport from Major Rivers to Puget Sound and Adjacent Waters

S.S. Embrey and E.L. Inkpen
U.S. Geological Survey

Historical data were compiled for the Puget Sound Basin study unit of the U.S. Geological Survey's National Water Quality Assessment Program to calculate nutrient loads transported each year from major watersheds to Puget Sound and adjacent waters. Major nutrient source loadings also were estimated to relate land use with watershed nutrient yields. With data from 24 water-quality monitoring sites, a computer program calculated average annual nitrogen and phosphorus loads for 1980–93.

Each year, rivers and streams transport 11,000 tons of inorganic nitrogen, 9,900 tons of organic nitrogen, and 2,100 tons of total phosphorus to Puget Sound and adjacent waters. Because of their large stream flows, the Skagit and Snohomish Rivers carry the largest nutrient loads. Nutrient yields per square mile of drainage basin, however, tend to reflect land use and development. The populous, agriculturally developed watersheds in the eastern half of Puget Sound Basin generally yield more nutrients than the less developed basins of the Olympic Peninsula. Yields up to 2.8 tons of nitrogen per square mile from the Samish and Nooksack River Basins correspond to source loadings of 9–10 tons of nitrogen per square mile from fertilizer, animal manures, and atmospheric deposition.

Marine Recreational Fisheries Statistical Survey (MRFSS)

Pamela Erstad ,Lori Takeoka, Sue Hoffmann
Washington Department of Fish and Wildlife

The Marine Recreational Fisheries Statistical Survey (MRFSS) program began in Washington State in 1979 through 1988 and recently began again in 1996. It is funded by the Pacific States Marine Fisheries Commission (PSMFC) and its purpose is to collect catch-and-effort information from marine recreational anglers along the west coast of the U.S. This information is very useful to recreational bottomfish managers because Washington state currently has no effective methodology for assessing recreational bottomfish harvests in Puget Sound. There are two components of the survey: an intercept survey that collects information on species composition and CPUE, and a follow-up telephone survey which is used to estimate total effort. In addition, information is being collected on bycatch, an issue that is becoming an increasingly important element of fishery management. Finally, the MRFSS Program collects economic information on what anglers are willing to spend on recreational fishing in Washington State. This data is extremely important because it provides information for resource managers, legislative bodies, and sportfishing organizations on the economic contributions of sport fishing. This in turn could help fund special projects with the aim of enhancing recreational fishing throughout the state.

The Importance of Combined Sewer Overflow Water-Quality Characterization in Bremerton's Combined Sewer Overflow Reduction Plan

Melinda J. Fohn and Kathleen Cahall
City of Bremerton Public Works and Utilities

With funds from a Washington State Centennial Clean Water Fund Grant, the City of Bremerton conducted two years of intensive water-quality monitoring of its combined sewer overflow (CSO) discharges. Flow-weighted composite and grab samples from 15 CSO sites were obtained and analyzed for typical parameters, including nutrients, metals, and organics. Results were compared to marine acute water-quality criteria and other nonpoint sources.

Discharge from a combined sewer system is composed of wastewater and storm water. The average wastewater component for each CSO site was determined. The concentration of ammonia and nitrates in the combined sewer sample was compared to an ammonia value representing 100% waste water. CSO sites had a wide range of wastewater component values, ranging from 1.8% to 37.5%. The wastewater pollutant loading for each CSO site into the receiving waters was determined using 1996 flow volume and percent waste water. CSO site pollutant loading reveals a more complete picture of the impact to the receiving environment of the different sites when compared to evaluation of flow volume only. The City of Bremerton realizes the importance of CSO-discharge water-quality information in prioritizing and evaluating CSO reduction projects.

Water Quality Goals for Lake Sammamish Derived from a Long-term Monitoring Program

Jonathan Frodge and Joanna Richey
King County Water and Land Resources Division

Diversion of sewage from Lake Sammamish in 1968 reduced the external load of phosphorus by about 35%. Lake Sammamish responded favorably to this nutrient diversion. Over a 5–10-year period, total phosphorus concentrations decreased from approximately 30–35 mg/liter to 15–20 mg/liter. During this period of lake recovery, summer concentrations of chlorophyll decreased from 3–4 mg/liter to about 1–2 mg/liter, with a corresponding increase in water clarity from about 3.3 meters to 4.5 meters.

These water quality gains are currently being reduced by increased nonpoint pollution from continuing development of the watershed. Since 1978 total phosphorus concentrations have increased from about 13 mg/liter (1978) to 22 mg/liter. Empirically derived water quality goals of 22 mg/liter volume weighted total phosphorus are expected to maintain average summer algae populations at current levels (2.8 mg/liter chlorophyll a), and should result in summer average water clarity of about 4.0 meters. If these water quality goals are maintained, beneficial uses in Lake Sammamish and downstream water quality in the Sammamish River will be protected. These water quality goals provide both a public education tool and a basis for the adaptive management of this watershed.

Production and Abundance of Heterotrophic Bacteria in Budd Inlet (WA) During Spring and Summer of 1997, and their Distribution Relative to Effluent from a Wastewater Treatment Facility

James Gutholm and Gerardo Chin-Leo
The Evergreen State College

Bacteria in the water column can be important contributors to the eutrophication of estuaries. We measured bacterial abundance (DAPI) and production ([3H]-Leucine) in Budd Inlet (WA) during spring and summer of 1997. This estuary is the southernmost inlet in Puget Sound and may be especially susceptible to eutrophication because of restricted tidal flushing. It also receives substantial nutrient inputs from the Deschutes River and from the wastewater treatment facility (LOTT) that services a large urban area. In spring, bacterial abundance ranged from 11.01 x 10^6 cells/mL to 3.85 x10^6 cells/mL, and bacterial production from 18.37 µg C/L/day to 4.73 µg C/L/day . These values are in the high range compared to other productive estuaries. To examine the possible enhancement of bacterial activity by wastewater, sampling stations included the area where treated waste water enters the bay. In spring, both bacterial abundance and production were significantly higher near the sewage outfall than at a site (Boston Harbor) 10 km away ($p>>0.01$). In summer, we increased the number of sampling stations near the LOTT outfall. During this period, even though both bacterial abundance and production were higher than in spring, no obvious trends were found with increasing distance away from LOTT.

Viral Hemorrhagic Septicemia Virus in Herring from the Puget Sound Spawn-On-Kelp Fishery

Paul Hershberger and Richard Kocan
University of Washington

Objective: To determine whether activities involved with closed pound spawn-on-kelp (SOK) fisheries contribute to active infections of viral hemorrhagic septicemia virus (VHSV) in associated herring.

Methodology:

- Phase 1: Wild herring from an SOK pound were sampled prior to impoundment and after 24 hr of confinement within the pound.
- Phase 2: Sexually mature herring were purse seined, transported to a net pen, and sampled from within the pen at 48-hr intervals. Tissues from all sampled fish were analyzed for VHSV via plaque assay.

Results:

- Phase 1: None of the herring (0/30) tested VHSV+ prior to introduction to the pound, while 12.2% (5/41) tested VHSV+ after 24 hr of confinement.
- Phase 2: None of the herring (0/100) tested VHSV+ upon introduction to the net pen but the percentage of VHSV+ herring increased to 17% (17/100) after eight days of confinement.

Conclusions: Activities associated with closed pound SOK fisheries are responsible for transfer and/or activation of VHSV infections among impounded herring. VHSV+ herring resulting from SOK activities may spread viral infections to wild fish due to:

1. The proximity of wild herring to the pounds, and

2. Release of VHSV+ post-spawn herring from the pounds.

Bull Kelp's Parasitic Brown Algae

Bruce Higgins
Marine Concepts

Typical methods for bull kelp (*Nereocystis luetkeana*) distribution and condition estimation may be missing health issues. It was reported in the 1970s that bull kelp can be infected by a parasitic brown alga. This parasitic condition can manifest itself in a variety of ways, but one that is obvious by visual exam is a warty external appearance. It may not have been widespread in the past, but has moved from rare or unusual to common at Edmonds Underwater Park, which adjoins a many acre kelp forest. Prior to 1992, this condition was rare, but starting with the 1993 season, native kelp and rafted kelp shows consistent evidence of this problem.

The condition appears to begin by a 5-cm stipe length and continues to persist throughout the life of the plant. It does not appear to influence the development of the blades or reproduction later in the season. It also does not appear to be stationary is space as kelp noted with the problem in one site does not appear to have maintained the condition the following year. This is a factor that may need to be included in future kelp census studies.

Island County/WSU Beach Watchers' Volunteer Intertidal Monitoring Program

Jan Holmes, Susan King, and Mary Farmer
Island County/WSU Beach Watcher Volunteers

Island County/WSU Beach Watchers are trained volunteers dedicated to protecting and preserving the fragile environment of Island County and Puget Sound waters through education and public awareness. The goal of the WSU Beach Watchers' Monitoring Program is to document in an accurate and meaningful manner the ongoing changes in beach profiles and biodiversity at specified beach sites following beach-monitoring guidelines.

The WSU Beach Watchers' program provides citizens an excellent opportunity to learn more about Island County beaches—about the plants and animals that live on a healthy beach and about the factors that might cause changes on a beach, either suddenly, or more slowly over time. Beginning in 1990, WSU Beach Watcher volunteer monitors have documented beach profiles and surveyed the numbers of plants and animals in the intertidal zone. The procedures have been field tested, standardized and streamlined until all volunteers, regardless of backgrounds, are able to understand and follow the guidelines after their initial training. The same monitoring procedures are applied to all types of beaches. The product, over time, is an expanding, quality controlled, baseline study of our island's beaches with data invaluable for the assessment of the health of our changing shores. The results of the development of the WSU Beach Watchers' beach monitoring program are currently being published as a Volunteer Monitoring Training Manual, including sections on Watershed Monitoring and Volunteer Training and Support. This manual will be shared with other environmental programs interested in developing volunteer intertidal monitoring programs in Puget Sound and beyond.

Ecological Functions of a Saltmarsh/Mudflat Complex Created Using Dredged Material at Jetty Island, Washington—The Final Verdict.

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Pentec Environmental, Inc

R. H. Gilmour and D. L. Gregoire
Port of Everett

The Port of Everett and US Army Corps of Engineers constructed a 15-acre berm using clean dredged sand to form a protected 19-acre mudflat. Four objectives were established for testing project success: 1) to balance erosion losses on the island, 2) to create additional dune grass habitat, 3) to create a protected embayment that would be colonized by marine invertebrates, and 4) to demonstrate a beneficial use of dredged material. Productivity and invertebrate biomass were expected to increase in the protected embayment, improving habitat for fish, shorebirds, and waterfowl.

Plantings of *Jaumea*, *Salicornia*, and *Distichlis* in 1991 flourished and achieved over 100% cover in some areas by 1993. Epibenthic zooplankton sampling in spring 1992 and 1994 showed higher abundances of juvenile salmonid prey species inside the berm than at comparable elevations on exposed shorelines along the remainder of the island. Beach seining in 1992 and 1994 demonstrated that juvenile salmon and other fish, especially juvenile surf smelt, use the embayment during high tides. The mudflat is intensively used by migrating shorebirds and bald eagles. Data from 1995 sampling demonstrated that the project met all pre-established criteria for success. Additional nourishment of the berm is planned in 1998 to maintain its physical integrity and preserve the ecological benefits.

Seismic Landslides in Puget Sound (SLIPS): Quaternary Faulting and Submarine Mass-Wasting

Robert E Karlin and R. J. Watters
University of Nevada

Mark L Holmes
University of Washington

Structure, stratigraphy, and geometry of Quaternary submarine landslides have been mapped from Everett to Tacoma using seismic profiling and side-scan sonar imaging. Massive submarine landslide complexes (>1 km wide) occur in several locations including Maury Island near Tacoma, Skiff Point (Bainbridge Island), Alki Point in West Seattle, Possession Point (Whidbey Island), Mukilteo, Edgewater, and Gedney Island near Everett. Ages of these slides are being determined by dating turbidite layers in piston cores. Submarine landslides are relatively common in the eastern passages of Puget Sound and tend to be better preserved than on land. Conversely, despite numerous coastal slides, western passages generally do not have submarine expression of mass wasting because of intense tidal scouring of the submarine slopes. Older Pleistocene units north of Seattle tend to fail as coherent blocks, whereas younger Esperance Sand/Lawton Clay units south of Seattle generally fail as incoherent slides, flows, and spreads. Many large slides in or near major fault zones appear to have been activated several times during the Holocene. Extensive Holocene thrust faulting and large landslides associated with the South Whidbey Island fault zone suggest that this area is tectonically active and may constitute a major seismic risk to the Everett-north Seattle area.

Geophysical Investigation of the Pacific Sound Resources

and Eagle Harbor SuperFund Sites, Puget Sound, Washington

Robert E. Kayen, Terry R. Bruns, Michael D. Fisher, Michael R. Hamer, and Homa Lee
U.S. Geological Survey

Chris Beaverson
NOAA Hazmat

The US Geological Survey, EPA, and NOAA acquired side-scan sonar, seismic reflection profiles, and bathymetry over the Eagle Harbor and Pacific Sound Resources SuperFund sites. Our objective was to spatially map units of potentially contaminated sediment placed offshore during operations at these sites. Our principal tool to acquire seafloor imagery was the Datasonics SIS-1000, a single deployable device with three channels supporting CHIRP side-scanning sonar and a downward-looking CHIRP sub-bottom profiler. Single-beam bathymetric surveys were conducted by the Hydrographic Section of NOAA to augment the geophysical dataset collected by the USGS.

Our investigation focused on addressing the following concerns: (1) determine the areal extent, thickness, and orientation of any potentially contaminated sedimentary layers; (2) ascertain any unusual characteristics or anomalies associated with the sediment surface or sub-bottom layers; (3) determine potential NAPL pathways associated with anthropogenic layers; (4) determine the extent of submarine structures. At Eagle Harbor, we additionally sought to characterize the morphology and spatial extent of the cap material placed on the harbor floor. For both sites, we found that the side-scan imagery, coupled with bathymetry, allowed for detailed description of the surface morphology of the sites, whereas, patchy zones of bubble-phase gas in the sediment-column hindered our efforts to observe the sub-seafloor stratigraphy in seismic reflection profiles.

Ichthyophonus Infections in Wild and Lab-Reared Pacific Herring (*Clupea pallasi*)

R. Kocan, P. Hershberger, and T. Mehl
University of Washington

Objectives:

1) Determine pathogenicity of *Ichthyophonus* for herring; and
2) Describe the natural history of *Ichthyophonus* in wild herring.

Laboratory-reared herring infected with *Ichthyophonus* spores began dying in 11 days. Skin lesions were detectable by 36 days, and by 56 days, 90% were dead. *Ichthyophonus* was cultured from all infected tissues. Infected tissues were injected into coast range sculpins (*Cottus aleuticus*), which became infected and/or died. Sculpins fed infected tissues became infected, while the controls did not.

Wild herring demonstrated skin lesions in 6%, 5%, and 4% of 0-year, 1+, and 2+ fish, respectively, while 6% 23%, and 52% of each group cultured positive for tissue-associated *Ichthyophonus*. There was no difference in weight or length between infected and uninfected fish.

Conclusions: Ichthyophonus is pathogenic for nonimmune herring, causing nearly 100% mortality. Lesions of the heart, liver, spleen, muscle preceded the appearance of skin lesions. Tissue culture appeared to be the most efficient method for detecting this organism.

Six percent of wild herring were naturally infected by 3–4 months old, while 52% of adults were infected. There was no evidence that the health or survival of wild fish were affected, but different environmental conditions or levels of infection could result in a significant level of morbidity and mortality.

Puyallup River Radio-Telemetry Study: White River Spring Chinook, 1996–1997

Russ Ladley, Blake Smith, Michael MacDonald, and Travis Nelson
Puyallup Tribal Fisheries

Chinook salmon, *Oncorhynchus tshawytscha*, with esophageally implanted radio tags were tracked in the Puyallup River system to determine movement patterns, migration hazards and spawning locations. A total of 272 adult chinook were tagged comprising 12% and 17% of the adult escapement above Mud Mountain Dam in 1996 and 1997, respectively. White River chinook were targeted by tagging fish at the Buckley trap located on the White River and those fish demonstrating early freshwater entry into the lower Puyallup River. Entry timing of White River stocks and summer/fall run hatchery stocks overlapped by six weeks. Movement, holding periods and holding locations varied widely among individual fish. The single greatest travel rate recorded was 32.5 km in 24 hours. The majority (75.5%) of the fish tagged moved through the lower Puyallup River (< rkm 17.3) within 14 days. Holding periods ranged up to 10 weeks. Males exhibited a higher propensity to move upstream and then back down. Most (74% of all redds) spawning took place within two non-glacial tributaries, but ranged from river km 18 to 89.8 of the mainstem White River. Redd elevations ranged from 45 to 853 m above sea level. Spawning occurred earlier within high-elevation stream reaches than in low-elevation reaches.

Development of Arsenic Speciation Data for Edible Biota, Sediments, and Water

Roseanne M. Lorenzana
USEPA, Region 10

A collaborative research project between USEPA Region 10 (Seattle) and the USEPA National Exposure Research Laboratory (Cincinnati) was started in September 1997. The objectives are (1) to develop a laboratory extraction method(s) for speciated arsenic in fish, shellfish and seaweeds which can be used with existing analytical arsenic detection methodologies; (2) in Alaska and Puget Sound samplesto determine concentrations and relative proportions of dimethylarsentate (DMA), monomethylarsonate (MMA), inorganic arsenic and organic arsenic and (3) to determine the effect of typical preparation and cooking procedures on speciated arsenic concentrations. The technical approach involves further developing analytical methodologies, collection of Puget Sound fish, shellfish, seaweed, water and sediments, analyzing the samples, and publishing an exposure assessment utilizing information from Puget Sound seafood consumption surveys (completed in 1996 (tribal) and 1997 (Asian Pacific American)). The expected outcomes include a standard operating procedure for assessment and validation of the quality of arsenic speciation data, publication documenting an extraction and analytical laboratory method, and publication of findings and a database which provides results of analyses in a manner that can be used in regional risk assessments.

Contaminant Monitoring of Surf Scoters near Tacoma, Washington as part of the Puget Sound Ambient Monitoring Program

Mary Mahaffy and Jeff Krausmann
U.S. Fish and Wildlife Service

Dave Nysewander
Washington Department of Fish and Wildlife

Adult male surf scoters were collected in Puget Sound near Tacoma, Washington in October 1995 and February 1996. Surf scoters are a relatively abundant winter resident seaduck in Puget Sound. Comparing the contaminant concentrations in scoters collected after they first arrive to those collected in the late winter allows an evaluation of contaminant exposure during the winter. Concentrations of mercury and chromium increased slightly in wintering scoters; however, they were well below concentrations known to cause negative impacts to birds. No appreciable uptake of polyaromatic hydrocarbons by the scoters was observed during their winter residency. General bird health was evaluated by examining a variety of tissue samples for lesions and conducting blood cell counts and serum chemistry. In general, the surf scoters collected appeared to be in good condition. The scoters were primarily feeding on mussels, clams, tube worms, and snails.

Association of Smallmouth Bass (*Micropterus Dolomieu*) Nests with Residential Piers in Lake Sammamish, King County, Washington

Roderick W.R. Malcom
Muckleshoot Indian Tribe

Freshwater piers may create habitat for predators of juvenile salmon or increase the interaction between salmon and their predators. Increased predation upon juvenile salmon may impair restoration efforts. To ascertain the potential for piers to increase the interaction between juvenile salmon and smallmouth bass, an introduced predator, 2.2 km of Lake Sammamish was surveyed by boat. Bass nests were located and the distance to the artificial inwater structure measured. Nearshore salmon use was determined by the spot beach seining and through analysis of other salmon use data collected in Lakes Washington and Sammamish. Smallmouth bass nests were preferentially associated with artificial in-water structure. Fifty percent of smallmouth bass nests were located within 2 meters of artificial in-water structure and 75% of nests within 11.5 m.

Though this study did not attempt to determine if smallmouth bass spawning is limited by lack of in-water structure, it did demonstrate residential piers and other artificial in-water structure provide focus for smallmouth bass spawning. Given the existing number of piers and ongoing construction rates, future research should quantify the impacts of piers upon the smallmouth bass population in Lake Sammamish and explore the association of other predators of juvenile salmon with artificial in-water structure.

Characterization of Groundwater Discharge into a Tidally Influenced Surface Water Body, Thea Foss Waterway, Tacoma, Washington

Daniel W. Matthews
Hart Crowser, Inc.

This talk discusses our methodology and presents preliminary results of our evaluation of groundwater discharge rates and associated chemical mass-loading rates into the tidally influenced Thea Foss Waterway. Because the Thea Foss Waterway is known to be a groundwater discharge area, mobilization of contaminants by flowing groundwater needs to be considered in evaluation of alternatives for remediation of contaminated sediments. The field program for the project included installing and sampling monitoring wells within and adjacent to the waterway, sampling recent marine sediments in the waterway, analyzing chemical partitioning between sediment and groundwater, sampling groundwater discharging to the waterway by means of well points and bottom flux chambers, monitoring water levels during a tidal cycle, evaluating groundwater salinity, and aquifer testing. The fate and transport of man-made contaminants dissolved in groundwater and adsorbed to sediments was estimated by several methods including numerical modeling techniques.

Environmental Limitations to Vegetation Establishment and Growth in Biofiltration Swales

Greg Mazer
University of Washington

To combat nonpoint source water pollution, federal and local governmental agencies throughout the country have required construction of "in pipe" stormwater quality improvement facilities. One such facility, the biofiltration swale (also called bioswale or biofilter), is an open channel possessing a dense cover of grasses and/or wetland plants through which runoff is directed during storm events. Aboveground plant parts (stems, leaves, and stolons) physically filter particulates and their associated pollutants as runoff passes slowly through the channel. Herbaceous cover is considered to be well correlated with treatment performance.

Environmental conditions and construction history were examined for eight biofiltration swales in King County, WA to determine relative importance of and threshold values for the various factors influencing vegetation establishment and growth. To improve future biofiltration swale design and performance, more consideration to providing seeded grasses with environmental conditions conducive to germination and establishment is recommended. However, even when installed properly, bioswales may not perform as anticipated in the long term if base and storm flows become channelized and/or base flow (inundation) persists through the growing season. Therefore, I recommend restricting biofiltration swales to very low flow (discharge and velocity) conditions and constructing large retention ponds and wetlands to improve stormwater quality under high-flow conditions.

Geologic Mapping in the Eastern Juan de Fuca Strait

David.C. Mosher, Kim Conway, Robert Kung
Geological Survey of Canada

Antony Hewitt
University of New Brunswick

High-resolution geophysical mapping in the eastern Strait of Juan de Fuca has led to the identification of three Quaternary geologic units: 1) till and diamict, 2) glacio-marine sediments, and 3) Holocene reworked sediments. Till is an acoustically amorphous unit and underlies most of the Strait. It is exposed at the seafloor in places, especially on the shallow banks. Glacio-marine sediments are typically layered and overlie till and outcrop over much of the seafloor. They have been extensively eroded. Holocene sediments consist of reworked glacio-marine and till material, since there is very little modern sediment input into the eastern Juan de Fuca Strait. This material is thin over much of the strait and thickens near banks, islands, and the coastline, areas where there is abundant sediment supply. This Holocene reworked material shows abundant evidence of strong current activity. Over much of the sea floor it is thin, forming a lag over older deposits, with bedforms developed on the surface. Adjacent to banks and coastlines it forms drifts and large sand waves. In one area south of Discovery Island these sandwaves are 25 m high and 500 m in width.

Two Years of Repetitive Side-scan Sonar Mosaics of the Point Grey Ocean Disposal Site, Vancouver, Canada

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Geological Survey of Canada

Dixie Sullivan
Environment Canada

One of the most active designated ocean disposal sites on the west coast of Canada is just outside Vancouver Harbor, off Point Grey in the central Strait of Georgia. The site, defined by a circle 10.78 km^2 in size, was officially designated in 1968, although dumping has been occurring in the region since 1938. It is in water depths between 210 and 250 m. Approximately 9.0 million tons of material has been dumped at the site since its designation. Repetitive sides-scan sonar mosaicing of the ocean floor, combined with video inspection using a remotely operated vehicle (ROV), are two monitoring tools used in this study. The intent is to investigate the impact of disposal on the sea floor, the rate of burial of disposed material, the dispersal rate of disposed material, and the amount of disposal occurring outside of the prescribed area. Digital geo-referenced mosaics allow for calculation of difference maps, which highlight newly disposed material. Approximately 85,000 m^3 of material were dumped during a one-month period between surveys. ROV observations show the disposed material to consist of wood-waste spoils, excavation material from construction sites, and bundle wire from saw mills.

Weak Osmoregulation Observed in *Cancer gracilis* (Crustacea: Brachyura) from Southern Puget Sound

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Although very abundant in the Puget Sound estuary at salinities near 25 g/kg (Kozloff 1996), *Cancer gracilis* is generally considered to be a coastal species unable to tolerate estuarine salinities (Jensen 1995). In order to investigate the osmotolerance of *C. gracilis*, we maintained crabs at 15, 20, 25, and 37 g/kg for an acclimation period of two weeks. Our results show that *C. gracilis* has a 100% survival rate at salinities of 20 and 25 g/kg. Hemolymph drawn from crabs acclimated for four hours to salinities ranging from 17-34 g/kg shows *C. gracilis* to be a weak osmoregulator at salinities from 17-20 g/kg, similar to previously published reports for *C. magister*. Osmoregulation was not observed after a 24-hour acclimation period, whereby the hemolymph of all crabs was found to be isotonic with the seawater. We also investigated the enzyme carbonic anhydrase (CA) that contributes to ionic regulation. Assays were performed on gill CA activities using the DCO2/DpH-method to obtain the CA activity of each gill. No difference was found in CA activities between gill pairs, indicating that there are no specialized performance patterns in the gills of *C. gracilis*.

Long-Term Patterns of Resident Orca Occurrence in Relation to Salmon in Puget Sound and the San Juan Islands

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The diet of the resident orcas that frequent the inland marine waters of Washington State and southern British Columbia has been shown to be dominated by a preference for salmon. The loss and/or severe reduction in salmon resources would be expected to correlate with changes in the pattern of occurrence of these orcas in the area. The year-round monthly occurrence of these orcas has been documented by pooling observations collected from public and private sighting networks in place in Washington and British Columbia since 1976 (N= 15,957). The most recent 15 years of this information has been coded as the number of days per month that resident orcas have been detected. Annual patterns of change were then assessed by month and compared with a) Washington State monthly salmon sport catch records, b) Fraser River sockeye and pink salmon run estimates, and c) for an overall trend that might indicate more recent changes in orca occurrence from earlier years.

Findings indicate that the resolution of this data is not high enough to significantly correlate the salmon measures with monthly orca occurrence relative to the orcas' year-round habitat, but it has documented a recent shift in their historical pattern. There is a higher occurrence of the orcas in the spring and a lower occurrence in the fall, as contrasted with an annually steady occurrence in the summer and winter. However, in 1997 there was a sharp increase in the fall occurrence of the orcas in Puget Sound, which is a significant departure from this trend, and may be indicative of food availability stress in this orca population.

Microhabitat Use by Rocky Reef Fishes in Puget Sound

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Scuba, video, and acoustic surveys have been conducted in Puget Sound, Washington State, since 1992. These surveys have identified major and minor habitat associations of principal reef fishes including copper rockfish (*Sebastes caurinus*), quillback rockfish (*S. maliger*), Puget Sound rockfish (*S. emphaeus*), kelp greenling (*Hexagrammos decagrammus*), and lingcod (*Ophiodon elongatus*). In particular, copper rockfish showed a high association with boulder fields and less usage of walls and rubble fields. Observed habitat associations may be in part the result of fishing and comparisons with patterns with fished areas and no-take refuges may help to identify the effects of fishing on habitat use by reef fishes.

Severity and Magnitude of Puget Sound Coastal Bluff Landsliding, 1996–97

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Active landsliding during 1996–1997 was observed along approximately 20% of sampled sections of coastal bluffs in northern Puget Sound. Recent landsliding (within the last 3–5 years) was observed along about 30% of the bluffs. Thus, about half of the sampled bluffs demonstrated active landslide evidence within approximately the past five years. In 1996–97, five people died, about 2% of homes were destroyed and many others sustained extensive damage. About 16% of remaining homes on or below the bluffs appeared to be at severe risk by having no (less than 10 feet) set back from the bluff top or bluff toe. About 60% of the sampled coastal bluffs are now developed, providing opportunity for improved development guidelines for the remaining undeveloped 40% of coastal bluffs.

In this investigation, aerial reconnaissance photographic sampling of coastal bluff landslides in northern Puget Sound on April 1997 was done to obtain a comparative evaluation of the magnitude and severity of coastal bluff landsliding. The sample is based upon east-facing bluffs (exposed to sunlight during the flight) of Kitsap and Jefferson counties from Bainbridge Island northward to Marrowstone Island, and of Magnolia Bluff in Seattle. The landslide activity in sections of coastal bluffs ranged from 6% to 36% of the 10 coastal bluff sections. Most of the homes on the bluffs appeared to be constructed closer to the edge of the bluffs than a 45_ slope extended from the base of slope.

Apparent causes of landsliding include glacial stratigraphic conditions, wave undercutting, concentrated and accelerated surface and underground drainage from above, uncontrolled land grading and vegetation changes, and triggering by natural seasonal storm events, especially those of greater that normal magnitude. The 1996–1997 storm was at least a 100-year event (USACE, 1997).

Trawl Survey Results in the Transboundary Waters of Washington and British Columbia

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Bottom-trawl surveys have been conducted in Washington since 1987, and in 1997, a synoptic survey was conducted in the transboundary waters of Washington and British Columbia. The surveys were designed to estimate numerical abundance of key benthic species, identify population trends, and quantify the impact of fisheries. The 1997 survey was also designed to describe the distribution of key commercial fishes that inhabit the Strait of Georgia but likely move between both sides of the international boundary.

Standard trawl-survey methodology was used to design the stratified systematic surveys. A 400-mesh Eastern Trawl was towed by a chartered fishing vessel. The bottom trawl is fitted with a codend net liner with a 1.25-inch mesh opening, and the trawl is towed at predetermined stations for 10 minutes. Trawl surveys were regionally based and at least 25 samples were taken each year. Five depth strata were designated as follows: 5–20 fathoms, 21–40 fms, 41–60 fms, 61–120 fms, and >120 fms.

Population trends will be evaluated as well as the effectiveness of survey design. The impacts of fishing will be discussed in relation to areas of heavy, little, or no commercial fishing.

Riverton Creek West Restoration Project: Partnership Approach for Habitat Restoration and Flood Control at an Urban Watershed

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City of Tukwila

Ira Dunbar, Denis Bourcier
Boeing

The Riverton Creek watershed drains approximately 430 acres and is located in Northwest Tukwila. The west tributary drains a small, forested area before crossing a major transportation corridor as it winds through the middle and lower watershed, which comprises residential and industrial areas. The east and west tributaries meet just upstream of the Duwamish estuary bridge at Route 599. The creek is subject to stormwater runoff originating from various land uses, including agricultural, residential, industrial, and transportation.

The objective of the current restoration project is to build on past efforts to combine revegetation and provision of in-stream habitat improvements into a multi-steward strategy that would increase fish habitat while reducing flooding potential at industrial operations adjacent to the creek. The stakeholders and users include the City of Tukwila, King County (KC), Tukwila Elementary School, WA Dept. of Fish and Wildlife, residents of the Riverton community in Tukwila, and Boeing Company employees. Additionally, the restoration parallels the Storm Water Pollution Prevention Plan BMP's for the Boeing facility as well as the watershed-wide plan for improvements currently being implemented by the City. Utilizing City of Tukwila as well as Boeing Company resources and volunteers, in addition to support provided to the city of Tukwila via a KC stream habitat improvement grant, the restoration project incorporates traditional revegetation methods with specific habitat improvements and physical barriers to sediment input to the stream. The resultant reductions in stream sediment loading and localized alterations have permitted the yearly installation of a salmon egg-hatching incubator and yearly releases of salmon fry that are being

raised at area elementary schools. Selective use of small sediment detention ponds and source control, combined with revegetation and in-stream habitat additions, have resulted in dramatic improvements in water quality and availability of habitat. This project provides an example of how an urban stream tributary can be upgraded and still meet flood control needs in a watershed that is subject to various contaminant and sediment loading sources.

Risk-Based Monitoring of Chemical Contaminants in an Intertidal Seep Zone

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As part of a five-year monitoring program along the shore of Liberty Bay, metals and semi-volatile organic chemicals were measured in ground water, seeps, sediments downgradient of the seeps, and shellfish. Groundwater transport and discharge results in exposures of marine organisms and humans to groundwater contaminants, particularly in the intertidal zone where groundwater directly contacts marine sediments and shellfish. Consequently, the monitoring program was developed to: (1) document the effectiveness of natural processes on attenuation of chemical concentrations in groundwater; and (2) develop site-specific measures of chemical exposure that could not be accurately predicted in a risk assessment. Samples were collected from over a dozen wells screened in surficial groundwater, two downgradient seeps, and nine sediment and shellfish (littleneck clams) stations arranged as a grid in the intertidal and subtidal zones. Along the shoreline of the site, spatial trends in cadmium and chromium concentrations were apparent in seep water, sediments, and clam tissues. Concentrations of chromium, cadmium, and several other chemicals in sediment and shellfish tissue were elevated above reference (EAR) area concentrations. The EAR ratios decreased along the exposure pathway from groundwater to sediments to tissues. These results indicate that sediment and tissue sampling are effective monitoring end points of ecological risk and natural attenuation of contaminated groundwater discharge into the marine environment.

Contaminated Sediment Disposal, Development, and Application of Siting Criteria in Bellingham Bay

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Mike Stoner
Port of Bellingham
Rachel Friedman-Thomas and Lucille Pebles
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The objective of this paper is to present a two-part process used by the Bellingham Bay Demonstration Pilot Project Work Group to blend participating agencies/entities goals, policies, regulations, and objectives into a process that identifies and prioritizes disposal sites for contaminated sediments in Bellingham Bay. Part One used exclusionary, avoidance, and cost screening criteria, along with available GIS databases, to identify a long list of 70 potential upland, nearshore fill, and confined aquatic disposal sites. Part Two involved the development of disposal site evaluation criteria and scoring guidelines relative to Pilot Project goals, and application of these scoring guidelines to the long list of disposal sites. Application of the scoring guidelines to the long list of disposal sites will be presented, along with a description of how final contaminated sediment disposal site alternatives were identified by the Work Group. These final disposal alternatives will be more fully evaluated in a forthcoming Feasibility Study and SEPA/NEPA EIS.

The Biosolids Handshake

John Poppe
City of Bremerton

The City of Bremerton constructed an 18-hole golf course in the 1960s. The demand for the facility provided the City an opportunity to expand the course in 1995–96 by adding another 18-hole course for public use.

Grade work and surface contouring began in the fall of 1995 and was completed early in 1996. The soil conditions were generally clay and sand with a predominance of fine sand as the final top mix. The fairways and greens were planted with grass seed from April through July 1996.

The sandy soil was very low in plant nutrients and had no organic content for water retention. Therefore, commercial fertilizer was used every two weeks as the nutrient source, with several water applications per day.

The anticipated growth (without biosolids) of the new turf prohibited course play until March 1997. The new course play schedule resulted in concern about the delayed time from the capital investment to the start of revenue by those playing the new course.

The City of Tacoma and the City of Bremerton have been developing the use of biosolids for various uses around Kitsap County for several years. This cooperation resulted in the City of Tacoma applying 361,000+ gallons at 5% total solids to 90% of the new Bremerton golf course.

As a result of the cooperative efforts of the Class A biosolids application, the new course opened on the Labor Day weekend of 1996. The revenue generated by the early opening is estimated to be $300,000.

Depositional and Erosional Mechanisms and Rates in Elliott Bay from Geological, Geophysical, and Historical Hydrography Data

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The objectives of this study were to determine the depositional and erosional environments in Elliott Bay, a Puget Sound embayment forming the Seattle waterfront, and to describe and quantify processes responsible for producing those environments. Hydrographic charts from 1935 and 1970, together with bathymetry profiles obtained in 1996 and 1997, were digitized and differenced to determine areas exhibiting significant changes in depth. Granulometric data for 500 previously collected bottom samples were analyzed to characterize depositional and erosional environments. Piston coring and reflection profiling were used to map seismic-stratigraphic units and examine subsurface stratigraphy. Paleobathymetric analysis shows the eastern marginal slopes of the Elliott Bay to be undergoing almost continual erosion, whereas the western slopes are characterized by depositional environments. The average net accumulation rate over the entire embayment was 0.6 cm/yr between 1935 and 1970. Episodic turbidity currents (~1/century) and submarine landslides have eroded into pelagically deposited sediment in outer Elliott Bay and along two inner submarine canyons. Bottom morphology and geometry of stratigraphic units suggest turbidity current velocities of 3–13 m/sec. The frequency and magnitude of turbidity currents and landslides suggest that care should be taken when choosing locations for sewer outfalls, submarine cables and pipelines, and dredge spoil disposal sites.

Toxic Response and Bioaccumulation in a Deposit-Feeding Polychaete—Relative Life-Stage and End-Point Sensitivity, and the Potential for Trophic Transfer

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This study provides a comprehensive set of baseline toxicity data that characterizes critical life stage responses of an animal with a typical marine life history, in long-term sediment exposures over a wide range of toxicant concentrations. The opportunistic, deposit-feeding polychaete *Armandia brevis* was exposed for 60 days to sediments supplemented with each of the toxicants dieldrin, pp'DDE, Aroclor 1254, fluoranthene, cadmium, copper, lead, and mercury. Mortality and emergence from sediment (an avoidance response) were recorded daily, and growth and maturity were measured at 20, 40, and 60 days. To assess recruitment, cultured planktonic larvae were presented with the same sediments as the juveniles and adults. All life stages of *A. brevis* proved amenable to laboratory experimentation. For all toxicants, the overall pattern of end-point sensitivity was growth (most sensitive) > settlement > maturity > emergence > mortality (least sensitive). The general rank of toxicant toxicity was dieldrin (most toxic) > pp'DDE = Aroclor 1254 = fluoranthene > copper > cadmium > lead = mercury (least toxic). Regression relationships between sediment and whole-body concentrations of organic compounds were linear, with bioaccumulation factors ranging from approximately 15 to 25. Overall, these results give insights into how anthropogenic chemical contamination may affect benthic marine ecosystems through differential effects on various life-history parameters.

Puget Sound Intertidal Habitat Inventory: Vegetation Mapping

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Puget Sound's nearshore habitats are a natural resource of significant value. The region's rapidly growing population continues to push habitat issues to the forefront for resource decision makers. The Washington State Department of Natural Resources, as part of a project to monitor the nearshore environment through the Puget Sound Ambient Monitoring Program, has characterized intertidal and canopy-forming vegetation in Puget Sound. This poster summarizes the inventory method used, and discusses the impact of geospatial detail on subsequent applications. Eight intertidal vegetation types were classified using multispectral imagery: eelgrass, brown algae, kelp, green algae, mixed algae, salt marsh, spit and berm vegetation, and red algae. The vegetation types encompass most common macroscopic vegetation found along Puget Sound's shorelines. Ground data, collected during the growing season, were used to guide the classification, or for classification accuracy assessment.

Comprehensive management of these important resources is best addressed by appropriately accurate and detailed information. The intertidal vegetation inventory provides information on the following characteristics of a feature: type, location, distribution, areal extent, shape/boundary, size range, and fragmentation. This high-resolution (4 m) inventory with polygon representation of features allows for detailed analysis of vegetation beds over broad areas, adding an important dimension to applications that analyze spatial relationships.

Elevated Levels of PCBs, PCDDs and PCDFs in Harbour Seals (*Phoca vitulina*) and Killer Whales (*Orcinus orca*) Inhabiting the Strait of Georgia, British Columbia, Canada

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We carried out a study aimed at assessing the levels of the polychlorinated -biphenyl (PCB), -dibenzo-p-dioxin (PCDD), and -dibenzofuran (PCDF) chemicals in free-ranging harbor seals and killer whales in British Columbia, Canada. Blubber samples were obtained from 43 harbor seals from three different areas in the Strait of Georgia. Pneumatic darts were used to obtain blubber samples from six known-age free-ranging killer whales from a southern resident pod, animals known to frequent Strait of Georgia waters, as well as 24 northern residents. Congener-specific analysis of PCBs and PCDD/Fs was carried out using gas chromatography-high resolution mass spectrometry (GC-HRMS). Concentration-age relationships were generated for males and females of both species. We estimated that a 10-year-old male harbor seal has 294 ng/kg of 2,3,7,8-TCDD Toxic Equivalents (TEQ) and 21 mg/kg PCB; a 15-year-old female has 118 ng/kg TEQ and 8 mg/kg PCB; while a 22-year-old male killer whale has 893 ng/kg TEQ and 106 mg/kg PCB; a 45-year-old female has 139 ng/kg TEQ and 22 mg/kg PCB in blubber (lipid weight). The lower levels in females of both species reflected the loss of contaminants to their calves during pregnancy and

lactation. We estimate that 3.3 kg of PCBs are distributed among the 30,000 harbour seals and 6.2 kg are distributed among the 96 killer whales frequenting Strait of Georgia coastal waters. Results suggest that contaminant levels may be high enough in some of the marine mammals inhabiting this coastal region of Canada to affect reproduction, immune function, and endocrine function, and that the killer whale population may be at particular risk.

Application of Multiple-Bioassay Interpretation Index to Four Interpretive Frameworks

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Body of a multiple-bioassay index (MBI) has been developed to evaluate results from abstract sediment bioassays and to provide a metric for facilitating sediment quality assessment. The index integrates the results of different bioassay tests into a single value, which represents the cumulative contribution of each test. The index allows for the explicit derivation of threshold levels for no adverse effect, minor adverse effects, and adverse biological effects consistent with regulatory criteria. The MBI is compared to four existing interpretive methods: Washington Sediment Management Standards, Puget Sound Dredged Disposal Analysis (PSDDA), USEPA/USACE negative control response method, and the reference envelope method of the California State Water Resources Board.

Caged-Mussel Pilot Study at the Port Alice Pulp Mill on Vancouver Island, B.C.

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Sandra M. Salazar
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An *in-situ* caged mussel pilot study was conducted to evaluate this approach as part of Environmental Effects Monitoring (EEM) at Canadian pulp and paper mills. The objective of the pilot study was to test the feasibility, scientific value, and applicability of using caged bivalves as a tool for EEM. Effects endpoints included survival, growth, percent water, and percent lipids. Exposure endpoints included mussel tissue chemistry and chemical analysis of lipid bags (semi-permeable membrane devices; SPMDs). To provide the option of including this methodology as part of Cycle 2 of EEM, the pilot study was conducted from August–October, 1997 at the Port Alice Mill pulp mill, Vancouver Island, B.C. Planning has been open to industry, government, and consultants. Representatives from each group observed and participated in the actual sorting, measurement, and deployment process. The scope of work included an element of technology transfer and the project was viewed as a combined Pilot Study-Workshop. The study will be evaluated based on previously established criteria such as: 1) scientifically defensible; 2) cost-effective; and 3) well-defined decision points. A significant relationship was found between proximity to the mill effluent diffuser and reduced mussel growth. Results show potential applications for monitoring effluents in Puget Sound.

Survival and Growth of Caged Mussels at 70-Meters Depth in Port Valdez, Alaska

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An *in-situ* field study was conducted to evaluate the feasibility and scientific value of using caged mussels as a monitoring tool to characterize chemical exposure and biological effects associated with the Ballast Water Treatment Facility (BWTF) effluent being discharged into Port Valdez, Alaska. A tiered approach was used; mussel survival and growth in Tier 1; chemical analysis of mussel tissues in Tier 2. Caged mussels (*Mytilus trossulus*) were transplanted at seven sites in the vicinity of the BWTF diffuser at a depth near 70 meters. Three hundred mussels were deployed for 56 days at each station; cages with individual compartments were used to facilitate measurement of individuals at the beginning and end of the test. There were no statistically significant differences in either weights or lengths by station at the beginning of the test. Mean survival of mussels was 97% and there were small increases in mean length (5%) and weight (7%). Growth results were similar to other mussel transplants in southeast Alaska and natural populations of intertidal mussels in the vicinity of the BWTF. The pilot study demonstrated that mussels transplanted to depths near 70 meters in Port Valdez will survive and grow so chemical analysis will proceed.

Long-term Trends in Willapa Bay, Washington from 26 Years of Oceanographic Observation: Effects of El Niño and Other Natural Cycles

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This study characterizes the natural forcing and responses of the physical-biological dynamics of Willapa Bay, a large estuary in southwest Washington. Data from the Washington State Department of Ecology's long-term Marine Waters Monitoring program (MWM) supplies 26 years (1973–present) of quasi-monthly measurements of temperature, salinity, water clarity, nutrients, chlorophyll-a, and fecal coliform bacteria. Recent data (1997–present) from an EPA-funded study of Willapa Bay conducted by the Washington State Department of Ecology provides additional measurements of temperature, salinity, water clarity, and chlorophyll-a concentrations at a much higher time resolution (15-minute). The MWM data provide a long-term perspective on the effect of seasonal cycles and several El Niño events on the dynamics of Willapa Bay. The EPA data capture the unfolding 1997–98 El Niño event, while resolving tidal cycles, weather, and runoff events. Fecal coliform bacteria levels are highest near river mouths and during rain-dominated seasons, as expected. El Niño events have had a variety of effects on Willapa Bay. The present El Niño is significantly warmer (by 2–3 _C) than any of the other seven El Niño events measured since 1973; its continuing effects on Willapa Bay are still being measured.

Asian Pacific American Seafood Consumption Study

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Objective: Data gaps exist in the characterization of seafood acquisition and consumption habits among Asian Pacific Americans (APA) because they traditionally consume different types and parts of seafood than the general United States public. This study documents APA seafood acquisition and consumption habits within 10 ethnic groups (Cambodian, Chinese, Filipino, Korean, Hmong, Japanese, Lao, Mien, Samoan, and Vietnamese) in King County, Washington.

General Methodology: To address these data gaps a two-year EPA Environmental Justice Community/University Partnership Grant was awarded to the Refugee Federation Service Center (RFSC) and the University of Washington, NIEHS Center for Ecogenetics and Environmental Health, Community Outreach and Education Program. A questionnaire was developed to characterize seafood acquisition, preparation and consumption. Study participants were randomly selected from volunteer lists, as well as community and church rosters. Bilingual surveyors used plaster seafood models to elicit more accurate seafood meal size estimates, and have completed a total of 200 survey interviews.

Results: Preliminary results were expected by February 1998.

Significant Conclusions: Pending.

Practical Applications: This study will provide valuable information about APA seafood consumption patterns in terms of types of seafood consumed, quantitative meal size estimates, and preparation practices.

Non-ionic Surfactants in Marine Sediments of the Strait of Georgia

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Toxic to aquatic organisms and suspected endocrine disruptive compounds, non-ionic surfactants nonylphenol and its polyethoxylates (NPnEO, n = 1–19) are being phased out in Europe. However, so far no data of NPEOs are available in North American marine environment. Using liquid chromatography coupled to electrospray ionization mass spectrometry, we developed a highly sensitive quantitative method to analyze NPEO concentrations in marine sediments. Five gravity sediment cores and 21 grab samples collected from Strait of Georgia were assayed for NPEO concentrations. NPEO oligomers with up to 19 ethoxy units were found in Strait of Georgia sediments at concentrations ranging from 10 to 960 ng/g (dry weight basis). The application of Principal Component Analysis on the NPEO data set shows a remarkably clear separation between the coastal and non-coastal areas. The significant result from the new soft-ionization MS analytical method—that the metabolites of the longer polyethoxy-chain nonionic surfactant are persistent in marine sediments—is contrary to previous conclusions that only NP_1EO and NP_2EO persist in the environment. The results of this work also suggest that a NPEO concentration mapping in the Puget Sound Strait is necessary to study the mobilization and biodegradation of NPEOs in sediments

and to assess the potential environmental impact of NPEOs.

Methods for Analysis of Triad Data

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The Triad approach to the measurement of environmental contamination generates multiple endpoints from three (or more) categories. A sample Triad data set might contain synoptic information collected on sediment chemistry data for a suite of chemicals, laboratory toxicity data for several sediment bioassays, and *in-situ* observations of the benthic community. The objective of the triad analysis is to identify any relationships present between the different legs of the Triad, and to interpret the risk level of individual sites based on the weight of evidence conveyed in the synoptic measures of the Triad data set. Typically, each of the endpoints are subject to different sources of variability and the relationships between the legs of the Triad are generally not very clear making interpretation difficult. We present a multi-step process for aggregating the information from all endpoints to provide a relative framework for interpreting stations based on the weight of evidence, and an absolute framework for distinguishing between individual stations. We use exploratory analyses to help select the individual endpoints; a randomization technique to indicate which stations are uniformly dirty, uniformly clean, or indeterminate; and multivariate technique to display the distance between stations. We present the results for a Triad analysis performed on data collected from a metals-contaminated aquatic site.

Bioaccumulation of Hydrophobic Organic Chemicals by Aquatic Biota with Low Lipid Content

Burt Shepard
URS Greiner

Equilibrium partitioning models are commonly used to predict organic chemical concentrations in both sediment and aquatic biota from the chemical concentration in water. For sediments, it is recognized that the partitioning relationship, and, thus, the predictive power of the equilibrium-partitioning model begins to break down at sediment organic carbon concentrations lower than 0.2–0.5% organic carbon. There is little if any information regarding the predictive power of the equilibrium-partitioning model for biota with a low lipid content. Partitioning of organic chemicals between sediment and a sea cucumber (*Parastichopus californicus*) with a lipid content less than 0.2% has been measured at several locations in Puget Sound. The measured sediment concentrations of organic chemicals have been used in an equilibrium-partitioning model to predict the chemical concentrations in sea cucumbers, which were then compared to the measured residues in the field collected animals. The model predictions in all cases were within a factor of 10 of the measured residues, and usually within a factor of four of the measured residues. Although the model correctly gives order of magnitude estimates of bioaccumulation in sea cucumbers, the model predictions are more accurate for animals with a higher lipid content.

Modeling of Propwash Effects on Sediment Capping Material

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Velocity produced by a ship's propellers can be a significant agent in dispersing bottom sediment under particular combinations of water depth, propeller speed, and details of the propeller itself. This paper reports recent studies in Puget Sound that have investigated applicability of equations describing propwash velocity to specific water depths and propulsion systems that define conditions near certain ferry docks of the Washington State Department of Transportation. Predicting disturbance of bottom sediment requires accurate knowledge of water velocities experienced near the sediment surface. A model was developed that incorporated recent research on propeller-induced velocity field, and that included certain calibration constants relating to the radial spread of the velocity jet behind the propulsion system. Field measurements were then made to evaluate the constants and verify the model. The result of this effort is a tool that has applicability in predicting the dispersion of sediment, contaminated or otherwise; in predicting the zone in which the disturbance would take place; or in determining the depth of scour that would likely occur in a sediment cap; or in defining the sediment size of the capping material that would resist scour under given vessel-operating conditions.

Plasma Vitamin A as a Biomarker of Contaminant-Related Toxicity in Free-Ranging Harbor Seals (*Phoca vitulina*)

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Captive harbor seals fed herring from polychlorinated biphenyl (PCB)-contaminated waters have exhibited reduced levels of plasma vitamin A, partly as a result of the physiological disruption of the transport mechanism of this essential nutrient. Contamination of the marine environment with PCBs has resulted in the accumulation of high levels of these fat-soluble chemicals in harbor seals and other top predators. As part of an ongoing ecotoxicological study, we are examining plasma retinoid concentrations as an indicator of contaminant-related toxicity in healthy, free-ranging, Pacific Northwest harbor seals. In a preliminary effort, we live-captured twelve 3–4 week-old harbor seal pups in the Boundary Bay area of southwestern British Columbia. Heparinized blood samples were collected from the extradural vein of each seal, stored at 4 _C in the dark until centrifugation, and plasma was cryopreserved at –80 _C until analysis. Existing methods were adapted to extract vitamin A from plasma samples and to quantify it using reversed-phase high-performance liquid chromatography (HPLC). Retinol concentrations for the 12 seals averaged 378 μg/L ±34.8 (range 210 to 568 μg/L), and replicates were consistently within 6% of each other. Having established these techniques, we will be monitoring the retinoid disrupting effects of contaminants on harbor seals at several sites in BC and Washington.

Effects Of Contaminants on Reproductive Parameters of Male English Sole (*Pleuronectes vetulus*) From Puget Sound, WA

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Effects of contaminant exposure on gonadal development in adult male English sole (*Pleuronectes vetulus*) from Puget Sound, WA, were investigated. Maturing males were collected from two urban areas (Eagle Harbor and Hylebos Waterway) containing high levels of sediment PAHs (polycyclic aromatic hydrocarbons) and PCBs (polychlorinated biphenyls), and two moderately contaminated non-urban sites (Colvos Passage and Pilot Point). Reproductive parameters including gonadosomatic index (GSI) and the plasma reproductive steroid, 1,1-ketotestosterone (a steroid involved in spermatogenesis), were compared to levels of contaminant exposure measured as biliary fluorescent aromatic compounds (FACs). Preliminary results showed that fish collected from urban areas had elevated levels of biliary FACs compared to fish collected from non-urban areas. No significant differences in reproductive parameters (GSI and plasma 11-ketotestosterone levels) were observed, and the proportion of maturing animals was similar between fish collected from urban and non-urban areas. Nevertheless, a few fish with high levels of biliary FACs had reduced GSI and plasma 11-ketotestosterone levels. In contrast to female sole, which have been shown to undergo reproductive impairment when exposed to these contaminants, males seem to be relatively resistant to contaminant exposure. However, sufficiently high exposure may have the potential to reduce gonadal development.

Merging Industrial SWPPP BMP's with P3 Initiatives: Solid Waste Compactor Pad and Decant Station

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Facilities improvements commonly address the aspects of both Industrial Storm Water Pollution Prevention Plan as well as WDOE-controlled Pollution Prevention Plans. The current project, which is the subject of this paper, provides both 1) a work area for compacting, weighing and separating solid waste; and 2) a decant station for street sweeper, storm water catch-basin, and oil/water separator clean-out waste. The combination of these activities at the solid waste pad result in a substantial waste reduction based on its in-ground aqueous waste separation capabilities, as well as the ability to segregate, weigh, and compact solid-waste materials in an enclosed area with stormwater pollution control.

Our previous research has characterized oil/water separator and catch-basin waste at two facilities such that the physical and chemical properties of the waste allow for separation of solids, oil fraction and aqueous component using simple solids settling and oil flotation designs. The system produces effluent concentrations of FOG, metals, and solids that are well below POTW criteria. A total reduction of over 700,000 pounds of hazardous waste at four Boeing facilities was realized, the installation of an in-ground oil/water separator will streamline the current process. The multiple use of the pad for solid waste activities provides the needed control and removal of debris which otherwise might pose a stormwater pollution risk, while at the same time providing the protected space for solid waste segregation and weighing.

Accumulation of Tributyltin (TBT) in Invertebrates and Fish from the Duwamish Estuary and Non-Urban Reference Areas in Puget Sound, WA

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Concentrations of TBT in invertebrates and fish were monitored by King County and the Washington Department of Fish and Wildlife in support of ecological and human health risk assessments of combined sewer overflows in the Duwamish River and Elliott Bay. Species monitored included English sole (*Pleuronectes vetulus*), quillback rockfish (*Sebastes maliger*), Dungeness crab (*Cancer magister*), bay mussel (*Mytilus trossulus*), and intertidal invertebrates, mostly amphipods (*Traskorchestia traskiana*).

Concentrations (wet weight) of TBT were highest in invertebrates and fish from the Duwamish River and Elliott Bay, and significantly lower in organisms from reference areas. TBT concentrations in sediments were also higher in the Duwamish River and Elliott Bay than in reference areas. Highest concentrations of TBT were found in the soft bodies of bay mussels (177.8 µg/kg) and crabs (81.9 µg/kg) from the Duwamish River and Elliott Bay. Concentrations of TBT in fillets of the longer-lived quillback rockfish from Elliott Bay (38.8 to 50.2 µg/kg) were significantly higher than concentrations of TBT in fillets of English sole from Elliott Bay (3.8 to 5.6 µg/kg). Concentrations of TBT in intertidal invertebrates (whole animal) from Kellogg Island in the Duwamish River ranged between 17.6 and 36 µg/kg, essentially the same range of concentrations measured in sediments at Kellogg Island.

Developing an Alternative Watershed Management Approach: Preliminary Results of Modeling and Measurements for Sinclair Inlet

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Puget Sound Naval Shipyard has proposed a project to EPA (through the Project XL framework) to create an integrated watershed management approach for Sinclair Inlet based on solid scientific research. This will involve comprehensive monitoring, computer modeling of the inlet and watershed, and an ecological risk assessment. This project will also incorporate extensive stakeholder involvement. Preliminary research has included three-dimensional computer modeling of Sinclair Inlet and initial real-time and ambient measurements of water quality and characteristics. This included metals, salinity, temperature, dissolved oxygen, currents, and others. This paper will present the early modeling results, data from measurements, and correlations between the model and data. The inlet hydrodynamics were shown to be dominated by tidal and wind forces, and demonstrated three-dimensional characteristics. This model will eventually be used to predict contaminant fate and transport and may be linked to surface water models to predict contaminant

loading. Additional monitoring of the watershed will be necessary over a long time scale to assess seasonal variations. The results of this project will be used to determine realistic TMDL's based on actual ecological impact and risk assessment, as well as developing an innovative, alternative regulatory approach to managing the entire watershed based on community goals.

A Large Outbreak of Vibriosis in Washington State, 1997

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Washington Department of Health

Vibrio parahaemolyticus is a naturally occurring bacterial pathogen that increases in marine waters and sediments during warm summer months. Large numbers of the organism in seafood can cause illness primarily characterized by diarrhea.

In Washington the number of confirmed cases of vibriosis has ranged between two and 36 cases per year since it became a reportable illness in 1987. In 1997 there was a marked increase in the number of vibriosis cases in the state, with a total of 57 laboratory-confirmed cases and 19 suspect cases reported to the Washington State Department of Health (WDOH). Oysters were identified as the most likely vehicle of transmission in 61 cases (89%), with 55 ill persons consuming them raw. Most cases (62) occurred in late July and August. California, Oregon, and particularly British Columbia had similarly high numbers of vibriosis cases reported during the same period.

The WDOH, along with the commercial shellfish industry, took several actions, including stricter shellfish handling procedures, voluntary closure of oyster beds, mandatory closure of some oyster beds, and issuing news releases advising consumers to eat only thoroughly cooked shellfish products. Results of environmental sampling during the outbreak showed levels of the organism below the regulatory action level. This suggests the action level should be reevaluated.

Use of a Flux Chamber to Assess Groundwater Recharge into a Tidally Influenced Water Body, Thea Foss Waterway, Tacoma, WA

Birgitta Willix
Hart Crowser, Inc

The flux chamber was designed to measure average groundwater flow into a surface water body and to collect time-averaged samples for chemical analyses. The design was based on David R. Lee's device and consists of an initially deflated plastic bag attached to a stainless-steel cone partially inserted in the sediments. Several modifications to Lee's design were added to ensure stability in a tidally influenced environment. Five chambers were placed in the Thea Foss Waterway in Tacoma. They collected water at rates varying between 0.02 and 1.57 gallons per day per square foot, showing significant variability in the groundwater flow. Salinity measured in the samples varied from 0 to 27 ppt. Groundwater in the Thea Foss Waterway area has displayed similar variability in salinity. Preliminary analytical data (analytical results have not been received from the laboratory to date) will be presented and its use in the evaluation of alternatives for remediation of contaminated sediments discussed.

Sediment Quality Changing At Cleanup Site along Seattle Waterfront

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In 1992 a layer of clean sand was placed over 4.5 acres to isolate or cap contaminated bottom sediments located north of the Coleman Ferry Dock and offshore of Piers 53–55. Repeated monitoring four years after cap placement show many changes in the surface sediments, but that the sand is still isolating underlying contaminated sediments.

Surface samples taken in 1996 showed that previously elevated levels of PAHs have decreased, while two new chemicals were detected that have not been previously found along the waterfront. The source of 4-methylphenol and phenol has not been determined, but both chemicals are used in a variety of products. Benthic taxonomy samples show the site is repopulated, but the benthic community has become more like the pre-cap community. This change may be partly linked to a greater percentage of fine-grained sediments in the remediation area.

Washington Department of Fish and Wildlife's Wetland Inventory Project

Robin Woodin
WDFW Habitat Program

Washington Department of Fish and Wildlife (WDFW) is addressing its role of wetland stewardship through first conducting a detailed wetland inventory of all agency lands. The information collected includes maps, classifications, noxious weed occurrence and extents, restoration and enhancement options, and adjacent land uses. Designed to benefit other potential users of this wetland information, the database includes a complete digitally mapped component (GIS coverage). The project began with the type of agency land having the majority of acres, the "Wildlife Areas," which comprise more than 700,00 acres statewide. Wildlife Areas have been purchased or brought under management through formal agreement for the purpose of managing for target wildlife or fish species. Consequently, the proportion of wetlands on these WDFW lands is four times greater than the total land base of Washington State.

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*PI = Plenary, PA = Poster Abstract

Appendix 2 (continued): Author Contacts

Name	Affiliation	Address	City	Postal Code	Voice	Fax	Sessions*
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Mark Myers	NOAA/NMFS	2725 Montlake Blvd. E	Seattle, WA	98112-2013	206/860-3329	206/860-3335	6B, 6B
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David Nysewander	WA Dept. of Fish and Wildlife	600 Capitol Way N.	Olympia, WA	98501-1091	360/902-2693	360/902-2162	7C
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Daniel Pauly	University of British Columbia	Hut B-8 Rm.100 2204 Main Mall	Vancouver, BC	V6T 124	604/822-2211	604/822-1201	7A
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Appendix 2 (continued): Author Contacts

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David Preikshot	University of British Columbia	Resource Mgmts. Environmental Studies	Vancouver, BC	V6T 1Z3	604/822-6224	604/822-9250	7A
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Scott Redman	Puget Sound Water Quality Action Team	PO Box 40900	Olympia, WA	98504-0900	360/407-7315	360/407-7333	PI, 3A, PI
William Reichert	National Oceanic and Atmospheric Administration	2725 Montlake Blvd. E	Seattle, WA	98112-2013	206/860-3329	206/860-3335	6B
Kyle Ren	UW School of Public Health	Box 357234	Seattle, WA	98195	425/673-1453		PA
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Appendix 2 (continued): Author Contacts

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Ralph Squires	Boeing Information & Communication Systems	Mailstop 46-87	Seattle, WA	98124-2207	206/544-2966		PA
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Appendix 2 (continued): Author Contacts

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*Pl = Plenary, PA = Poster Abstract

Appendix 2 (continued): Author Contacts

Name	Affiliation	Address	City	Postal Code	Voice	Fax	Sessions*