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PUGET SOUND

RESEARCH '91

WELCOMING ADDRESSES AND PLENARY SESSIONS

WELCOMING ADDRESS

Christine Gregoire
Chair of the Puget Sound Water Quality Authority and Director of the Washington Department of Ecology

Good morning, and welcome to **Puget Sound Research '91**. Continuing a tradition begun in 1988 with the First Meeting on Research in Puget Sound, this conference will present to you the latest in the study of the Sound and the problems it faces.

Puget Sound, indeed, faces a number of severe challenges. Three million people live in the Puget Sound Region. Over the next twenty years another million and a half are expected to join them, drawn by the quality of life and the environment. That growth will make addressing Puget Sound's problems even more difficult. Currently, we can identify signs of strain and poor management, based on that population: toxic chemicals in urban bays, closed shellfish beds, destroyed and degraded wetlands.

As policy makers working to stay ahead of the challenges compounded by that growth, we rely on a solid understanding of the Puget Sound ecosystem, an understanding supplied by research and now updated by the findings revealed at this conference over the next two days. The research results tell us where best to invest our taxpayers' dollars to preserve our most important and renowned natural resource in the state of Washington: Puget Sound.

I would like to spend a couple of minutes talking about the commitment to that investment in the Sound. The creation of the Puget Sound Water Quality Authority in 1985 brought focus to the state's role in this effort. The Authority is charged with preparing and overseeing the implementation of a comprehensive, coordinated plan to protect the Sound. The plan includes measures aimed at cleaning up the pollution already there and, most importantly and most effectively, a long-term solution of prevention in the first place.

The 1991 plan was adopted in November and will be printed next week. It builds upon the progress made in carrying out the 1987 and 1989 plans and contains new programs in estuary management and fish and wildlife habitat management and protection. This new plan calls for stronger programs in spill prevention, monitoring, municipal and industrial pollution discharge reduction, nonpoint pollution control, and stormwater management. The 1991 plan also lays out a strategy for the creation of the Puget Sound Foundation. This foundation would be designed to fund and coordinate research and education programs on the Sound. As everyone attending this conference well knows, funding for vital research has been inadequate. The Puget Sound Foundation, we hope, will play an important role in meeting that need.

The Puget Sound Water Quality Management plan is a national model, and Washington State is now America's leader in estuary management. Of the seventeen estuaries in the country recognized as having national significance, Puget Sound will be the first to have a comprehensive plan. In a few weeks we will present EPA Administrator Bill Reilly with the Puget Sound plan. It will guide both state and federal actions over the next four years. It is an accomplishment that each and every one of us can be proud of.

Far more than in planning, though, Washington State is a national leader in the investment in *doing* the job of cleaning up and protecting the Sound. We are now carrying out programs in education and public involvement, monitoring, shellfish protection, nonpoint pollution control, and municipal and industrial discharge reduction. The 1991 legislature will also be considering a new and innovative program for oil spill prevention.

These are lean budget times across the country and here in Washington State. In competition with the pressures from other programs, those lean dollars are vital to us in the cleanup of Puget Sound. Governor Gardner has taken a bold step in increasing the funding for Puget Sound protection. He has submitted a proposal to the legislature that more than doubles the state funds now dedicated to implementing the Puget Sound plan. State spending would increase from approximately $16 million in the current biennium, to approximately $35 million over the next two years. This is a strong commitment. The Governor recognizes that a modest investment in prevention now will help us avoid huge outlays to clean up Puget Sound in the future.

By way of example, think if you might about Commencement Bay. Had we been more diligent, had we been more visionary, had we taken prevention as our first and foremost effort in Commencement Bay, it would not be a federal superfund site today. Prevention *is* the key. And strong programs in municipal and industrial pollution discharge reduction, oil spill prevention, stormwater runoff control, and nonpoint pollution reduction are the tools we need to protect the Sound and prevent any further degradation.

But those programs obviously cost money. Thanks to the Governor and our legislative supporters we have made a good, solid beginning. We will need the support of our friends in the legislature, of everyone in this hall, and of all the people across the state, to ensure that Puget Sound funding survives the legislative process and emerges from the session as proposed by the Governor.

The state is not alone in working to protect the Sound. Local and tribal governments, operating under tight budget constraints, have made solid investments to assist in cleaning up and protecting Puget Sound. In addition, many citizens, through trade associations, constituent groups, community groups, particularly in the schools, businesses and individuals, have given

their time, their creativity and their solid support to the preservation and cleanup of Puget Sound.

On the federal level the leadership of the Environmental Protection Agency has been key. The EPA, in working with other federal agencies, has fostered a cooperative relationship with the Authority as we have crafted the estuary management plan for the Sound. EPA deserves credit for its strong commitment to making the process work. Their assistance in helping the Puget Sound plan become a national model of how to protect our marine environment has not gone unnoticed by the state of Washington and it is greatly appreciated.

It is my pleasure this morning to introduce to you the administrator of the EPA's northwest region, Dana Rasmussen. Dana has a strong background in regulatory law. She is a graduate of Stanford University, and the University of Oregon's School of Law. For the past several years she has served as Assistant Vice President and Chief Council for Federal Relations for US West. Before that she worked in private practice, and as a congressional aid on energy and environmental issues. It is was just six weeks ago that she officially assumed her responsibility for directing the Environmental Protection Agency's full range of activities in Alaska, Idaho, Oregon and Washington. As a native northwesterner, she shares our understand and appreciation for the Sound and for our precious natural environment.

I have had the opportunity to get to know Dana over the last couple of months, and I can assure you that we are very lucky to have an individual with this kind of talent and this kind of commitment to lead the Environmental Protection Agency here in Seattle and for the Pacific Northwest. We look forward to working with her, and with the other federal agencies in the Puget Sound cleanup.

Please join me in giving a warm welcome to Dana Rasmussen.

WELCOMING ADDRESS

Dana A. Rasmussen
U.S. Environmental Protection Agency Regional Administrator

On behalf of EPA I would like to congratulate the Department of Ecology, the Puget Sound Water Quality Authority, and all the other agencies who worked so hard and so well together over the past several years on the Puget Sound Water Quality Management Plan. It is truly one of the leading efforts in the nation to develop a plan to protect a unique body of water such as Puget Sound.

It is also very heartening today to see this well attended meeting on Puget Sound Research; it shows a reaffirmation of commitment of all of you to the important issues facing the Sound.

Chris Gregoire has already so articulately delineated some of the state commitments to the Sound and the initiatives that are going forward within the Department of Ecology and with Governor Gardner's proposals to the Washington Legislature. On behalf of EPA I want to also reaffirm our support of this program.

Puget Sound is one of the 17 estuaries participating in the federal National Estuary Program and is the first one to have completed and adopted an environmental management plan. That plan was adopted by the Puget Sound Water Quality Authority on November 21 and, with Governor Gardner's concurrence, will be submitted to EPA Administrator Bill Reilly for his review and approval within the next few weeks.

We all know that planning is an important first step, but plans must be implemented before environmental benefits are achieved. The Puget Sound Program has been a leader in this area as well.

Programs to address some of the obvious problems were initiated in parallel with the planning process back in 1985. The result is that...

the Urban Bay Action Program, which was designed to control toxic inputs to the Sound, has made substantial gains;

a Sound-wide monitoring program is up and running;

an excellent public education and involvement program is in place;

and sediment standards for toxic materials have been developed for Puget Sound.

No other estuary in the United States has progressed as far in terms of accomplishments.

The efforts of all involved in the Puget Sound work over the past 6 years have set the standard for all other estuary programs across the country. The partnership that was forged with federal, state and local agencies, as well as interested individuals, is one of a kind.

During the past 6 years EPA has been proud to have funded and managed over 100 studies and projects which have contributed to the plan. Some of these studies will be discussed at today's research conference. These studies, which were conducted by state, federal, and local agencies, were part of EPA's $10 million commitment to Puget Sound.

Where do we go from here? Now that the plan is completed, EPA's role will be one of continued support. We will provide funding to help facilitate the implementation of this plan and will continue to be active in supporting programs for wetland protection, non-point source pollution protection, NPDES permit oversight and assistance through EPA's standard programs.

In these programs we hope to look at new directions—emphasizing risk-based priority setting, and raising the importance of ecological risks, in addition to health protection risks. We will also encourage pollution prevention to keep contaminants from even entering the environment.

We will work with federal facilities, including the Department of Defense, to assure that they have the assistance they need to do their share to keep Puget Sound as environmentally strong as possible.

In summary, EPA is proud of being part of this team which worked with strong commitment and dedication to help assure preservation of the quality of Puget Sound. A conference like this provides a great opportunity to share the results of the work as well as exchange ideas. We look forward to working with you these next two days and also in the future. Thank you very much.

INTRODUCTION TO THE PLENARY SESSIONS

David Jamison
Chair, Committee on Research in Puget Sound

Good Morning. On the behalf of the Research Committee I would like to welcome you, and hope that you have a good two days full of interesting talks and discussion.

Puget Sound Research '91 is known by another name, and that is the "Second Annual Research Meeting on Puget Sound," just one year late. As you can guess, it is a very time-consuming and costly effort to produce these affairs, but we have had some tremendous help from Tim Ransom and Diana Perl to put this event together. I would also like to acknowledge the individuals who sat on the Steering Committee for this event: Bruce Miller, Alyn Duxbury, Sheri Tonn, Jacques Faigenblum, and Don Haring. We also would like to acknowledge the financial help of the agencies and companies that helped us put this on.

Unfortunately we have not been able to bring these meetings to you with the frequency that we should be. Hopefully with the [Puget Sound] Foundation coming into being in the near future, that frequency will increase.

I note, and you have heard it several times, that a thousand folks may be coming here today. I hope that reflects an increased interest in Puget Sound, because the last meeting had 700, and that it is not just a reflection of growth of population of the area.

I have been given the honor today to introduce you to the first in a series of talks on "perspectives" on Puget Sound. These talks will be given by distinguished citizens of the Pacific Northwest from a variety of points of view. The intent is to initiate and facilitate a dialogue on Puget Sound, its resources, and management. For it is only through a frank and continuing dialogue between managers, scientists, and the public that we can come together to insure that Puget Sound can continue to provide for our needs, without damage to its long-term viability.

Our first speaker is known as a scientist's scientist. Marsha Landolt is not only well known in her area of expertise, but her broad perspective on the larger issues in science, as well as on the management of science, has led to her appointment as associate dean of the College of Ocean and Fishery Sciences at the University of Washington. In addition, since 1975 she has been a professor in the University's School of Fisheries, where she teaches graduate courses in fish and shellfish pathology. Dr. Landolt is the author and co-author of more than 50 scientific papers concerning the effects of pollutants

on aquatic organisms. She has done considerable work on Puget Sound pollution including, several years ago, moderating a session on toxic chemicals at the First Puget Sound Research Meeting.

Dr. Landolt will be speaking on "Puget Sound Research: a Scientist's Perspective," and I understand that she is going to give us an interesting and challenging perspective.

A SCIENTIST'S PERSPECTIVE

Dr. Marsha Landolt[1]

For the past few years, scientists in the United States have been engaged in a heated debate over the proper allocation of federal research funds. The argument centers on the proportion of resources that should be spent on "big science"—the Hubble telescope, the human genome project, the super-conducting super-collider—versus the proportion of resources that should be spent on "small science" — the investigator-initiated grants, training grants for students.

While the stakes are clearly much smaller, a similar debate is simmering among scientists here in the Puget Sound region. Today I would like to take this occasion to bring that debate from a simmer to a boil.

Over the past 10-15 years, small, investigator-driven research on Puget Sound has been supplanted by large, agency-directed projects, such as PPSDA, Superfund, Home Port. Projects that many people in this room, including myself, are involved in. This type of "big science" clearly offers advantages.

First, it is relatively low risk. One can be pretty sure of getting results, and pretty sure of not being a candidate for the Golden Fleece Award. Second, there is a high degree of accountability. The sponsor is able to maintain close control over the project and to assign a technical representative to monitor progress and ensure that the investigators are on track. Third, there is a high degree of uniformity. It is possible to standardize protocols and to insist on uniform types of equipment, so that data are comparable across projects. Fourth, these projects generate large quantities of data. Fifth, the reporting requirements are prearranged. This allows the sponsor to know what he can expect to receive at the end of the project in the form of deliverables and reports. Finally, this type of research is very useful. It provides information that is critical for regulatory matters, permitting actions, remediation efforts, and legal challenges.

As you can see, there is much to be gained from this type of work, and I am not here today either to condemn it or to dismiss it. However, when this is the *only* type of work that is being done, we are missing out on opportunities:

1. We are missing *the opportunity to apply the scientific method* to research on Puget Sound. The incredible advances that have occurred over the last century in fields such as medicine, engineering, and bio-technology have

[1] College of Oceans and Fisheries, University of Washington, MS HN-15, Seattle, Wa 98195

been firmly rooted in experimentation. But here, when confronted with difficult problems, challenging questions, complex issues, we have been too willing to limit our activities to data-gathering exercises because they are safe. We describe conditions, we measure concentrations, we conduct bioassays, we compare one site to another, we look at terminal effects — we do the same projects, over, and over, and over again with only minor variations.

Rarely do we test hypotheses. Rarely do we attempt to understand mechanisms or to look at processes. Rarely do we look at system-wide issues, rather than site-specific ones. Rarely do we take advantage of the experiments we conduct when doing public works projects. You know, every public works project that is undertaken in this state is required to have an environmental impact statement. That impact statement tries to predict the effects that will occur, it basically puts forth a hypothesis. We are not taking advantage of the opportunity to retrospectively test the hypothesis. Was it right? Why wasn't it right? Can we explain what we didn't understand?

The real hope for understanding Puget Sound as an ecosystem, for understanding how contaminants are transported, how they get into animals, how they affect them, is based on experimentation and the scientific method. We must use it.

2. We are missing *the opportunity for creativity.* In traditional research efforts, the investigators, using the scientific method, develop a hypothesis and design a series of experiments to test it. This process is dynamic, it's creative, it's a joy to observe. Scientists brainstorm ideas, they play "what-if" games. What if we do this? What if we do that? What if we are *totally* wrong about this and something else happens? From those brainstorming sessions come ideas — bright ideas, stupid ideas, wild ideas. We need some creative ideas for Puget Sound.

Right now, creativity plays a relatively small role in the research that we are doing. In many of the studies we are engaged in, the sponsoring agency predetermines the work that is to be done, specifies the measurements that are to be taken, specifies the protocols that are to be followed, and specifies the equipment that is to be used. Sometimes the scientist can play a creative role in the actual sampling design, but for many projects the research proposal is little more than a pricing bid.

In preparing this talk, I wanted to be sure that you heard more than my biased perceptions, so I talked with a number of scientists whose work I hold in high esteem. I talked with people in the University, in governmental agencies, in private business, and asked why they had dropped out of Puget Sound research or had never gotten involved in the first place. In large measure they replied that the work simply isn't interesting. They countered, however, by

saying that Puget Sound itself is fascinating, that the questions remaining to be answered are intriguing, and that they would be anxious to get involved if a door were opened to do creative research. We need to recruit those scientists into this effort.

3. We are missing *the opportunity to take pride of ownership.* In a traditional research project, the investigator bears the responsibility for failure, but also gets to take credit for success. There is a pride of ownership that comes with a job well done. In many of our research projects, this sense of ownership has been lost either because the task is parcelled into such small work units that the investigator doesn't really have a sense of the overall project, or because some of the work is so *pro forma* that scientists serve as technicians.

Let me give you an example. In the past year I was asked to provide histopathological analysis in support of two large projects. In both projects the field work—the external examination of the fish, the necropsies, the tissue collection and preparation—were done by someone else, someone I never met! I played no role in the project design, I never met the other investigators, I never really knew how my sub-project related to the other sub-projects or, for that matter, to the long-term goals of the total project. I stand firmly behind the work I did, but I never developed any *investment* in the project. I felt no personal involvement. I simply received boxes of slides to examine. That was unfair to me, because I didn't get the opportunity to grow professionally. It was also unfair to the sponsor, because I didn't have the opportunity to contribute the knowledge I have gathered during the past 20 years.

4. We are missing *the opportunity to utilize the talent that is available* in the Puget Sound region. Within our universities, government agencies, private companies, we have access to expertise in fisheries, oceanography, civil engineering, ecology, medicine, botany, toxicology—you name it, its within driving distance. With that pool of talent, we should be able to assemble dream teams of researchers! Instead we allow ourselves to get caught up in contracting regulations and laws that constrain our ability to utilize the best talent.

Again, let me give you an example. A few years ago I was sitting in my office at the University when the telephone rang. An employee of one of our state agencies informed me that his agency had become aware of unexpected contamination in a particular area. The agency was worried about possible effects of that contamination, and wondered if I would be willing to examine the health of resident animals. I said I would be delighted to collaborate. Then they said, "Ok! We will have to put an ad in the Commerce Business Daily and you will have to write a proposal....." At that point I realized that the system had gone awry. The caller represented a state agency, I represented a state agency, why couldn't we collaborate without elaborate contortions? Why do we get caught up in complex contracting interactions that stifle, rather than encourage us to work with the talent that is here?

5. We are losing *the opportunity to make a lasting contribution to science.* Science is a constantly evolving process that is built upon the contributions of individual investigators. The legacy of science is passed from one scientist to another, and from one generation to another, through publications, museum collections, archives, students, etc. If we were to critically examine the money we have spent on Puget Sound research, the energy that all of us have poured into it, and the volume of paper that we have produced, what would we identify as being the lasting contributions to science?

I worry that most of the data we have collected over the last decade will sit forever in huge, undigested final reports. I worry that less than five percent will *ever* be peer-reviewed and shared with the larger scientific community through publication in the open literature. Why does that happen?

First, the type of research we are doing has such burdensome reporting requirements that by the time we arrive at the end of a project and have written all of the quarterly reports, annual reports, final reports, we are totally burned out on the project and are already looking for the next project. A second reason this information doesn't get disseminated is that there never is time or funding at the *end* of a project to bring the investigators back together to distill the essence of what was actually discovered. Finally, much of the work is so site-specific, so parochial, or of such limited interest that many journals won't accept it. Those three factors combine to keep the information under wraps.

I also worry that the energy that we have expended collecting specimens over the last decade is going to be lost. I worry that we will not see museum collections or archives built around our efforts, and that we will find the material scattered over so many locations that it will essentially be lost.

Finally, as an educator I worry that relatively few graduate students will be produced as a result of our efforts. It was disturbing to learn from the organizers of this conference that they had a difficult time locating student papers. That shortage of papers may reflect that students are shy, but I worry that it results from the fact that few students have been involved in the research.

6. We are missing *the opportunity for passion.* When scientists are allowed to test and develop hypotheses, to be creative, to take credit for their work, to collaborate with talented people, and to make a lasting contribution to science, they become passionately involved in what they are doing! They talk about it incessantly! They care about the work and can't wait to find out what is going to happen next! I don't see a lot of passion today when I talk with people who are working on Puget Sound issues.

So how do we turn this situation around? We have to forge a partnership involving agency personnel, scientists, and persons involved with the legislative process. To those of you who are involved with the legislative process, I encourage you to do what you can to create a mechanism that will allow us to fund research. Whether that mechanism is the Puget Sound Foundation or some other vehicle, do what you can to foster research.

To those of you in government agencies, I ask that you take full advantage of the talent that is here, that you encourage innovation in the projects you fund, that you open the door to unsolicited research proposals, that you listen to what scientists are saying about research priorities, and that you give scientists the opportunity to function at the very limit of their capabilities. I ask further that you challenge the contracting system. Try to find ways to make it simpler, to facilitate communication and sharing, to tear down the barriers. Finally I ask that you consider accepting publications in lieu of final reports.

To my fellow scientists, I have several challenges. First, it is time for us to be leaders, and not followers. *We* have to identify the important questions, and *we* have to see to it that they receive attention. Second, we have to stop accepting mediocrity. If a project is not worth doing, we need to have the courage to say, "This really is not worth doing." And finally, we need to look ourselves square in the eye and determine the degree to which we are guilty of perpetuating the *status quo* because we go out and churn the system, looking for work.

If all of us come together we can continue the work that is underway, but we can also open the door for "small science" and for big ideas.

PUGET SOUND: A POLICY PERSPECTIVE

Dr. Robert L. Bish[1]

When Tim Ransom approached me to be a speaker here at Puget Sound Research '91, he indicated that "attitudes" were to be a major theme of the conference. Because "attitudes" are emerging as a key variable in analyses of institutional arrangements to deal with common pool resource problems world-wide, I agreed to pull together some ideas that help place what is happening here on Puget Sound into the perspective of on-going resources management research. I also believe the success of efforts on Puget Sound have significance for environmental policy far beyond the Puget Sound Region.

My observations on the importance of attitudes in resource management are really conclusions which I will return to. First, I am going to summarize the key features of politics and government here in the Puget Sound Region and in Washington State. Second, I will summarize some of what is being learned about the management of common pool resources, an area of scholarly research that has really developed world-wide in the past few years. Then I will indicate some important gaps in knowledge and a dilemma scholars face when examining institutional arrangements such as those that exist here in the Puget Sound Region. At that point, I am going to argue that "attitudes" are a key variable to fill a major knowledge gap. Finally, I am going to indicate why attempts to govern Puget Sound with pluralist, populist, democratic institutions is important, not only for the future of Puget Sound, but for everyone's future in dealing with environmental problems.

GOVERNING PUGET SOUND

In *Governing Puget Sound* and in my 1983 presentation to the Puget Sound Water Quality Conference, I described the nature of the governing philosophy and institutional arrangements here in Washington State. These arrangements include:

- a very open democratic, pluralist, populist, system of government with many elected officials, the initiative, referendum and recall;
- a multiplicity of governments, from single purpose special districts through municipalities, counties, regional arrangements, state agencies and federal departments, including both advocacy agencies and adjudicatory ones;
- many coordinating arrangements including contracts, joint arrangements, referrals, standing committees and ad hoc committees—supplemented

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since 1983 by the Puget Sound Water Quality Authority as an important forum dealing specifically with Puget Sound; and,

- a very high level of citizen participation in the entire system.

The Washington State political system represents the extreme of a participatory democratic system. Access is open and easy and there is no center of authority.

I also indicated a very important research finding: that in the similarity of attitudes and preferences between elected officials and citizens, Washington State ranked 42nd highest of the 50 states. This is, of course, the kind of match one would hope for in a democratic system.

INSTITUTIONS FOR COMMON POOLS

There has been an explosion of research on institutions to manage common pool resources in the past few years. This research encompasses world-wide examples, most of which involve water resources of one kind or another. It has also involved the creation of a world-wide community of scholars, the International Association for the Study of Common Property, who come together to discuss their problems and findings. During the past year, I have had an opportunity to review and discuss many of the studies. If there is any one thing that stands out from the hundreds of case studies compiled, it is that the relatively simple approaches developed in biology, engineering, economics, planning and resources management do not consistently identify the important variables that are related to performance, let alone provide a basis upon which one can confidently recommend specific institutional arrangements to manage specific common pool resources.

I am not saying that these discipline-based approaches have never served to provide a basis for successful resource management. What I am saying is that sometimes they do and sometimes they don't. In short, our understanding of key variables is incomplete. I found the research results surprising. I thought we had a better understanding of the dilemma's involved in managing individual common pools and external effects.

Let me give you a simple example of what I mean:

Canada has an "ideal" model of fisheries management: there is one Federal government department, the Department of Fisheries and Oceans (DFO), with excellent fisheries scientists and a hierarchy of field fisheries managers. It is a well established agency under a parliamentary form of government where no national government rises or falls on the basis of fishery management, and scientists and managers are allowed to manage.

However, a continual stream of evaluations of the results of fisheries management point to one disaster after another. During the past two years, for example, the east-coast off shore fishery has collapsed, the B.C. abalone fishery has collapsed and it is now forecast that at least 10 years of no-fishing will be required for recovery (this is after 10 years of intensive management by DFO), several important lobster fisheries in the maritimes have been disrupted by DFO regulations imposed from the outside on a successful traditional system of management, there is sufficient capital equipment in the B.C. herring fishery to take the annual catch in less than one day, and the B.C. clam fishery is in major decline from damaging and too frequent harvesting practices. While the department blames Europeans for the problems in the east-coast fin fishery, lobster, abalone and clams pose relatively simple management problems. The biggest successes in Canadian fisheries management are with some Fraser River stocks, stocks which are jointly managed with the U.S., not by DFO alone.

I do not want to pick on Canada's fisheries management, but simply to use it to indicate that the institutions that experts have proposed to achieve good common pool resources management do not always work, and we do not always know why. At the same time, researchers have identified successes where none of the attributes of a modern scientifically based bureaucracy exist, and while I believe modern science is necessary in modern resources management, many many studies, world wide, indicate that science and bureaucracy are not sufficient.

One can also ask, what are characteristics of some institutions where modern management is missing, yet resources are well managed. A variety of these kinds of situations have been identified, but again, not with consistency. Most successes involve relatively small, traditional communities which worked out solutions to problems over long periods of time in relatively stable environments. Unfortunately, many apparently identical communities have also failed to manage their common pool resources.

One can only speculate about what is missing that is necessary to predict whether or not institutional arrangements will be successful in resolving common pool problems. Before I proceed to such speculation, I want to turn to more complex environments such as are faced in Puget Sound.

INSTITUTIONS FOR MULTIPLE-USE RESOURCES

Two things are really different on Puget Sound, compared to the research environments common pool research has focused on. First, there is a multiplicity of uses and users; and second, there is a multiplicity of organizations that are not subject to centralized control. Here we have two problems to reconcile: first, can we anticipate any single organization to be successful, i.e.

will METRO get the sewage treated or will it operate like Canada's DFO; and second, will the multiplicity of organizations interact with one another so that the multiplicity of uses and users is accommodated while maintaining a reasonable natural environment?

I have already indicated that we cannot be sure that a single scientifically-based organization will consistently manage successfully. We are even less sure of what makes multi-organizational systems work.

The first systematic study of multi-organizational systems was of markets as they emerged from feudalism and mercantilism. Mandeville, Smith and others observed that as societies and economies became more complex, the Crown could not manage adequately, and that markets comprised of a multiplicity of competitive firms and consumers would work better. Those who have not learned this suffer, as in the Soviet economies.

However, markets work well only under certain conditions, the most important of which are that market prices reflect values and opportunity costs. When prices reflect values and opportunity costs, they provide bits of information upon which individuals within very large and complex multi-organizational systems make decisions, and the entire system functions in a reasonably coordinated manner.

Well, our problem on Puget Sound is more complicated. We have a multiplicity of uses, users and organizations, but we do not have explicit prices for many values and opportunity costs to apply to the use of Puget Sound's resources. Furthermore, given the common nature of the resources, there is no feasible way to obtain prices to reflect all values and costs, even though we reveal values and incur costs in every decision. This leaves us with a second resource management question: in addition to what variable is missing from studies of common pool management we also need to know what takes the place of prices to aid in coordinating uses and users of Puget Sound's resources. The question of what replaces prices in helping to coordinate complex multi-organizational systems is an important one, not just in resources management, but in a wide variety of policy problem areas.

I propose the same answer to both resource management questions. My answer is that the level of shared attitudes and values among participants in a system is a key variable that is missing from research on common pool resources and is critical for coordinating multi-organizational systems.

THE IMPORTANCE OF SHARED ATTITUDES

The concept of shared attitudes has several dimensions. It is not just similar preferences, although that is one component.

First, and most important, one must be able to "put him or herself in another's place." For example, the regulator must be able to put himself or herself in the place of a person affected and understand the implications of the regulation from that person's perspective. Or, a person who uses a resource for one use, say water transport, must be able to understand the perspective of a person who uses the resource for another use, say fishing or swimming. This condition of empathy with others is useful, but not critical in markets. I think it is critical in complex non-market settings.

Second, and closely related to putting oneself in another's place, is respect for others: a recognition that while there are significant differences among people, there are also similarities. In short, while we can put ourselves in another's place, we also share a respect for them that is reciprocated. This reciprocality means that each person treats another person's preferences as important.

Third, people have to have some similarity in preferences, at least for the use of common resources, and fourth, people have to feel that their decisions make a difference—both in how their use impinges on a resource and in that their preferences are taken into account in the system. It is hard to conceive of effective common resource management if people's preferences are totally different, or if each feels his or her use and preferences make no difference.

One very important implication of these attitudinal variables is that they apply to politicians, scientists, administrators, resource users and the public together. That is, different actors must share an ability to put themselves in the other's place, they must respect each other, they must have common preferences regarding the resource, and they must feel that their actions make a difference. These shared attitudes will then make it possible for scientists to focus on critical questions, for politicians and administrators to make decisions which reflect public values, and for users to moderate their demands relative to one another. A similarity of attitudes among persons in different roles is most likely to occur in a very open political system and it is least likely to occur in a system where isolated scientists and managers make decisions for others. Without such shared attitudes I cannot see why or how a multi-organizational resource system, such as that governing Puget Sound, would work. Shared attitudes should also make it easier to govern any single common pool, as well as help achieve coordination in a Puget Sound-like situation.

While I think there is a good case for the importance of shared attitudes in the management of resources, there are several difficulties with the concept. Each of the variables comprising shared attitudes has a potentially wide range and we do not know "how much" of each is required. We also do not know how tolerant the system is of free riders. Experimental economics research indicates that systems do not collapse with a few free riders, but if a threshold is

crossed destruction of the common pool resource occurs rapidly. The real world is likely to be similar.

Equally important is that we do not know if attitudes are policy variables. That is, can we design policies that produce shared attitudes, or, do attitudes just evolve in some systems but not in others? For example, why do so many share common attitudes toward Puget Sound? There are nearly two million people around the Sound. If we didn't share attitudes that have led to such conferences as this one, could they be created? Or are we in a situation where we may discover that shared attitudes are important, or even critical, for common resources management, but we do not have the ability to create them, except by means of the creation of a propaganda machine? While I believe shared attitudes are very important for resource management, questions like these will require serious research.

THE IMPORTANCE OF PUGET SOUND

What happens in Puget Sound is far more important than the health of Puget Sound itself. What is being done here is the governance of an extremely complex natural resource for a multiplicity of uses and users with a very open democratic political system. We have a test of whether or not democratic systems with wide-spread citizen participation can combine with science to successfully manage the environment. Alternatives do not look good. One alternative is to abandon democratic values to environmental technocrats, and such recommendations have been made, but the evidence of successfully managing simple common pools is so mixed that there is no reason to expect that technocratic management will be successful with even more complex problems. The other alternative is to fail, to one degree or another, which does not auger well for dealing with larger potential environmental crises in the world at large. Continuing to successfully govern Puget Sound in an open political system would provide powerful evidence that disastrous alternatives are not our only choices.

I have always been impressed that the energy with which citizens, politicians, administrators and scientists approach governing Puget Sound. It is a system that seems to capture the best efforts of each; a system where participants appear to have a high degree of understanding of others, respect each other, care for the natural environment, and feel that their actions make a difference. Washington's very open political system has provided an institutional environment very suitable to its task. The Puget Sound Water Quality Authority also makes an important contribution to promote this sharing, as does the sponsorship of this conference by so many different organizations. This is precisely the kind of forum where we can learn to put ourselves in each other's place and transmit the kind of knowledge and sharing of values that I believe are so necessary for continued success in governing Puget Sound.

PUGET SOUND: THE PUBLIC'S PERSPECTIVE, OR "WHAT'S THE POINT OF PUGET SOUND?"

Daniel Jack Chasan [1]

When I chose "what's the point of Puget Sound?" as a subtitle, I assumed some people would be offended by the idea that Puget Sound has—or needs—a "point." The Sound is a part of nature. It just is. The water just is. The killer whales just are. And so on.

Well, I think that's disingenuous. Of course, on one level Puget Sound simply is. But that's not our level. We are, after all, human beings—human beings living in the late 20th century, no less. To us, Puget Sound has economic values, recreational values, aesthetic values, symbolic values. The problem—if you want to call it a problem—isn't that we live in a capitalist society or that most of us are heirs of European civilization. True, we have technologies and markets that give us the power and incentives to do things that people in other times and places might never have imagined. But that's just a matter of tools and opportunities; the crucial fact is simply that we're human.

Am I saying that the Sound should be viewed primarily as an economic cornucopia? Not at all. In fact, I'll argue that while we originally saw the Sound that way, our view of it has changed radically over time, and by now, we value it even less for economic reasons than we think or pretend we do.

Our values have changed. Therefore, Puget Sound's value to us has changed. But because we do have those late-20th-century tools and opportunities, the Sound will be largely what we want it to be. The choice is ours. Whatever our choices and whatever our values, we should recognize that people have used the Sound all along. Native cultures used it as a source of food and a medium of local transportation. Early non-native cultures did the same. But the goal of early non-native settlers was never just subsistence. They wanted to sell things to the outside world. (The native communities did, too; people of the coast traded Puget Sound fish and shellfish with people of the interior.) The main thing they had to sell was trees. Huge trees. The closest major market was San Francisco. The only way to get first-growth Douglas fir logs from here to there was to float them. From the beginning, every milltown where people cut first-growth trees with single-bitted axes and lived among the stumps was linked by sailing ships to California, Hawaii, China. And from the beginning, non-native communities valued the Sound as a conduit for economic development.

We still have ports, of course, but this was different. The water let everyone be

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an economic optimist. Any community on a natural harbor was basically as close to the timber supply and to the markets as any other. Therefore, any muddy little milltown could hope that with a few lucky breaks, it would become the next New York or Boston or San Francisco. The Sound could bring economic development to any shore.

That belief, that hope, that pipedream didn't last long. It started to change when the transcontinental railroads arrived. All of a sudden, if you wanted to reach an eastern market, being closer to the railhead was crucial. For some towns the Sound started becoming a barrier to economic growth. I think that began a process of historical evolution that has culminated in our current attitudes toward Puget Sound.

Let's skip forward a few decades—that's all it is—from the coming of the railroads to the start of World War One. The War formed a permanent dividing line. Around Puget Sound as in the nation as a whole, it really marked the break with the 19th century, the space between pre-modern and modern.

Here, from the perspective of 1991, it is even more of a dividing line. It marks roughly the halfway point for Washington as a political entity. Washington Territory was created in 1853. The halfway point between then and now was 1921. The border with Canada, which made Puget Sound unequivocally part of the United states was settled in 1846. That pushes the halfway point back to 1918. Either way, at least half the history of Washington has taken place since World War One. (And, by the way, since the founding of Boeing in 1916.)

What was happening in that first decade after "The Great War?" For one thing, people were driving cars. The automobile had been around for decades, but it really caught on during the war. By the 1920s, while boats still carried a lot of people and a lot of stuff around Puget Sound, they were secondary. The automobile was the big thing—and getting bigger. There's a lot of nostalgia about the mosquito fleet between the wars, but the fact remains that by that time, it was on the way out. The Sound had definitely become less a highway than a barrier.

Another thing that happened in the 1920s was construction of the first sulphite pulp mills. The mills did not represent the first more-or-less modern industry on the Sound—the soil on parts of Vashon Island, where I live, still contains lead and cadmium that were deposited by the Tacoma Smelter, which started roughly 40 years before—but they did represent the first modern industrialization. And they did emit wastes that were generally—and rightly—considered nasty.

Oyster growers had warned from the start that pulp mill effluent would be bad for shellfish. No one paid much attention. Even then, in the good old days,

shellfish were locally important, but they didn't represent very big business on the Sound. Pulp mills, on the other hand, represented the largest concentrations of capital and employment the region had ever seen. They stood for industry, progress, economic development. It was just too bad about the oysters.

Just as the oystermen predicted, the mills started up and the shellfish industry declined. Was this cause and effect? The oysters certainly had other problems, including the silting up of their beds and the appearance of a predator called the oyster drill. No oyster grower ever proved his case against the pulp mills in court. On the other hand, the mills made out-of-court payments to oyster growers, and under laboratory conditions, pulp mill effluent certainly proved unhealthy for oyster fry.

All this started in the 1920s. I'm going to throw another timeline at you: Washington celebrated its centennial two years ago. Therefore, its halfway point as a state was 1940. Therefore, pollution of the Sound has been an issue more than half the time Washington has been a state.

World War Two was another great divide. Shipyards boomed again. People came. The Boeing Company mushroomed.

After the war, a lot of things were different. The era of cheap local water transportation was definitely gone. The Black Ball Line, which ran the ferries on the Sound, wanted to raise rates. There was a great public outcry. To make a long story short, the state acquired the ferry system in 1951. Then it quickly raised the rates. If the change had been at all obscure before, it was obvious now: The Sound would no longer bring economic development to anyone's front door.

At the same time, the rise of Boeing started to shift the regional economic balance. After the war, Boeing was far and away the largest single source of jobs. The mills were still important locally, but regionally, they were no longer the 800-pound gorilla.

Through the 1950s and most of the 1960s, they remained the main focus of environmental concern. But the state started requiring them to get discharge permits, and then, in the 1960s, even told them to clean up, although the state never had enough backbone to enforce its own deadlines.

At the end of the 1960s, though, the focus suddenly changed: Nineteen sixty-nine began with the Santa Barbara oil spill. The environment became a national issue. That all coincided, more or less, with the news that a huge oil field had been discovered on Alaska's North Slope, and the start of an epic environmental battle over construction of a Trans Alaska Pipeline from the

North Slope to Valdez. After oil left the pipeline at Valdez it would have to go somewhere, and that somewhere might turn out to be Puget Sound. As the 1970s began, the spectre of supertankers on Puget Sound became the leading environmental nightmare.

Not that other issues had gone away. The pulp mills were still controversial. The state had never forced them to clean up, but now, the federal government got into the act. Local economics no longer made a compelling argument. The mills could clean up or shut down. Most of the mills did clean up. The rest did shut down. Some companies blamed plant closings on environmental regulation, but that was always pretty questionable; the new requirements may have moved up the day of reckoning, but the mills that shut down were antiquated plants unable to compete.

Economically, the early 1970s were tough times for Puget Sound. The "Boeing bust," during which the Boeing Company laid off nearly two-thirds of its workforce, lasted from 1969 through 1971. Statewide unemployment peaked at 15 percent. Not an ideal time, one might think, to pass a sweeping new environmental initiative. But one would be wrong. A state Shorelines Management Act got enough signatures in 1971 to qualify for the ballot, and it went before the people in 1972. It passed handily—not the version preferred by environmental groups, to be sure, but a landmark law nonetheless. Voters in eastern Washington rejected it. But voters around Puget Sound voted yes. Even in tough times, or with the memory of tough times fresh in their minds, people were no longer thinking of shorelines primarily in terms of economic development. The water and the shoreline were valued for other things.

Certainly, they weren't valued for their ability to attract a major oil port. People still wanted to keep supertankers out. In the mid-1970s, the state legislature passed a "tug escort law" saying that without certain safety features, any big tanker inside the Sound needed a tug escort at all times. The Supreme Court eventually ruled that unconstitutional, but Washington's late Senator Warren Magnuson slipped a law through Congress that prevented construction of a major oil port on the inner Sound. A private poll showed that 85 percent of the adults in Washington approved of what he'd done.

At first, many environmentalists who opposed an oil port pushed the idea of building a Northern Tier pipeline under the Sound as an alternative. As the threat of supertankers faded, though, the pipeline replaced them as an environmental issue. Finally, then-governor John Spellman decided once and for all against the Northern Tier pipeline proposal. Commenting on this decision, I remember *The Wall Street Journal* described him as a kind of environmental wacko. He was, of course, a very low-key Republican governor—his detractors would call that an understatement—doing what most of his constituents evidently wanted.

Which brings us into the last decade. O.K.: We're in the 80s. No supertankers. No pipeline. The surviving pulp mills have all installed secondary treatment. But there are still some worms in the apple. In fact, as the decade begins, a couple of rather disturbing things catch people's eyes. First, Tacoma's Commencement Bay is declared one of the ten worst toxic waste sites in the country. Then, we learn that you don't have to be in Commencement Bay to find toxic substances in the sediments. And we learn that fish living among the sediments have liver lesions.

These findings, disturbing though they are, don't inspire any great public enthusiasm to "save the Sound." That requires two other events. One is the death of two whales in 1984. There is no reason to believe pollution has killed them, but some people say pollution has killed them, and dead whales turn out to be pretty spectacular attention getters. At about the time the whales show up, the *Seattle Times* runs a series about pollution in Puget Sound. The *Times* hasn't discovered anything new, but by giving the Sound big-deal treatment, the paper transforms a situation into an event. "Saving the Sound" starts taking on the trappings of a crusade. Nineteen eighty-five is billed as "the year of Puget Sound" in the Washington legislature. It looks as though big things are about to happen.

Well, looks are deceiving. The legislature does reestablish the Puget Sound Water Quality Authority—at that point a short-term study group—as a long-term institution with responsibility to monitor, report on and—most important—create a plan for water quality in Puget Sound. But the legislature doesn't come up with money for the program. And it doesn't do anything else.

The next year, the legislature does find a source of money for water quality programs. Cigarettes. It raises the cigarette tax, with the proceeds to be used for both Puget Sound and groundwater programs. This is not exactly a ringing financial commitment. But at least it's something.

And the crusade to save the Sound? What crusade? There is, I think, a consensus that people care about—and will do something about—water quality in Puget Sound, but realistically, you get people's attention with a disaster, an impending disaster, the threat of a disaster. By and large, the Sound is in pretty good shape. The Authority's plans have been designed to keep a relatively good situation from getting worse. This is a groundbreaking effort. It is rational. It is prudent. It is not sexy. With an emphasis on regulations and monitoring and long-term funding, it doesn't quite appeal to the emotions. It doesn't inspire the multitudes.

And the multitudes didn't rise up in revolt last year when the legislature changed the structure of the Water Quality Authority over the protests of all its members. It may be indiscreet to mention this here—and I have no wish or

reason to run down the Authority in its present form—but the incident was politically significant. For good reasons or bad, the legislature was responding more to industry than to the clean water community when it decided to change the Authority's structure and move the Authority's office to Olympia. Now, you can argue that these changes won't make the Authority any less effective. You can argue—some people do—that they should actually make the Authority more effective. But the fact remains that the members of the Authority, the Authority staff and a lot of the people who have pushed clean water for years didn't think so. And their objections were brushed aside.

Does this mean clean water is losing its constituency? I don't think so. People still value Puget Sound. In fact, people still put the idea of a clean Sound on a pedestal. It is a regional icon. We all believe in it.

But when you get beyond iconography, beyond basic right thinking, any resemblance between popular conceptions and reality is purely coincidental. The same polls that have shown a public commitment to clean water have shown that most of the public thinks industry is responsible for the problems, and industry should pay the bills.

Obviously, industry is still responsible for some problems, including the contamination of sediments. Now we realize that pulp mills emit dioxins. Now, we should realize that if we're going worry about oil development offshore, we should worry about the statistically greater danger of routine tanker shipments into the Sound. ut industry is no longer the whole story. When we look at non-point-source pollution, it's not even much of the story. From the start, the Authority has pointed out the significance of non-point pollution—"lifestyle pollution," if you like: septic tanks, agricultural runoff, stormwater running off roads and parking lots. I like to call this a classic example of the old Pogo line: "we have met the enemy, and he is us."

This means it is no longer useful to simply round up the usual suspects. Where's the bad guy? Where's the painless source of funds?

Some non-point problems are easy enough to deal with. People don't want to pollute Puget Sound, so if you do some education, and you make some public money available to, say, help a farmer buy fencing to keep his cattle out of the stream, you can accomplish a lot.

But it's not always that easy. There are thousands upon thousands of septic tanks. There are major land use issues. If you try to deal with stormwater, you run into horrendous physical and financial problems. And whether you're talking about stormwater or septic tanks, you have to ask, just how much of their own money are people willing to pay to keep pollutants out of Puget Sound?

And for what? For shellfish? Shellfish have become major symbols of clean water. That's natural. And it's appropriate. But it has become tangled in a number of distortions. In the first place, is the issue the welfare of oysters or our ability to harvest and eat them with impunity? I'm as anthropocentric as the next guy, but I have to recognize that there's a difference. From an oyster's point of view, coliform bacteria may be a blessing: they won't kill you, and they just may keep you from being eaten. So when we talk about the effects of non-point pollution on shellfish, let's not pretend we're concerned about the oysters themselves; we're saying that we value one human use of the Sound—shellfish harvesting—over another—dumping wastes.

Economics have of course been used to justify clean water policies for years. Often, this has been well-intentioned sophistry. But it has contained, or has seemed to contain, a kernel of truth. Twenty years ago, people were talking about the Sound's potential for aquaculture as a reason to keep supertankers out. That was evidently one of the things that motivated Warren Magnuson in the late 1970s. Even more recently, people have talked and written as though shellfish were a huge business that had to be saved from the ravages of pollution.

Well, $16 million a year worth of clams and oysters—which I'm told is a preliminary figure for 1989—isn't peanuts, although it's certainly not enough to justify the money that has been and will be spent on clean water here.

And the old argument about the Sound's potential for aquaculture has collapsed. Now, many environmentalists have started fighting against the expansion of aquaculture here. For political reasons, a vast expansion isn't likely to happen. There are legitimate questions about the environmental effects of raising Atlantic salmon in floating net pens in Puget Sound. But those questions aren't what has made the progress of aquaculture here so very slow. The main problem is that owners of waterfront property don't want aquaculture blocking their views. And owners of pleasure boats don't want it blocking their way. I know some people who oppose aquaculture on serious environmental grounds will argue with this. Some have argued with me in the past. But look at the facts: floating net pens for salmon aren't the only form of aquaculture that has run into opposition. It has also been hard for people to clear the legal and political hurdles necessary to raise oysters or abalone or seaweed.

This is, I think, the logical extreme of the idea that in most places, the Sound has become a barrier to keep economic development away. Of course, the Sound still brings in foreign trade; the large ports are flourishing, and no one is talking about shutting them down. And of course the Sound brings in the tourists; it is also an integral part of the "quality of life" that brings in people who work in high-tech and other industries.

To attract people, we need a Sound that is perceived as being clean. But, to be cynical, how clean is clean enough for that? I think the answer is, the Sound is clean enough whenever we say it is. When someone flies here from, say, Los Angeles or Cleveland to vacation or to buy a house, is he or she really going to know—or, probably, care—about the chemical makeup of sediments dredged from the mouth of the Duwamish River? Is he or she really going to dig clams on some stony beach south of Tacoma? Get serious. Most visitors will see the blue water and the mountains, maybe take a ferry ride, maybe buy a salmon at the Pike Place Market. That's about it. If our papers and our television newscasts are full of people saying the Sound is a sewer, they'll be repelled. But if the water's clean enough for us, it'll probably be clean enough for them, too.

Am I saying we should ignore the problems or even deliberately deceive people about water quality in Puget Sound? No. Of course not. I'm just saying that unless things get very, very bad—a lot worse than they are now—the link between water quality and economics is pretty tenuous. And that's OK. The 80s are over. We don't have to look at "the bottom line." After all, is that why we're here? Let's face it: We want a clean Sound for aesthetic reasons, cultural reasons, spiritual reasons. We want it because we think we should want it. We want it because it's the right thing to do.

But, especially in a recession, will the body politic spend money for something that's not perceived as a foundation of economic growth? Let's turn that around. How much will the body politic spend for something that has been touted up and down as a foundation of economic growth? People have been trying to sell education that way in Washington State for years. Has it worked? Are we lavishing money on public education? On the universities?

People either believe a clean Sound is important, or they don't. For reasons that may have little or nothing to do with economics. For intangibles. Still, it's legitimate to ask: How deep is our commitment to these intangibles? How much are we willing to spend for them? Can we stay focussed on them into the next century? I certainly hope so. Stay tuned.

PUGET SOUND

RESEARCH '91

ISSUES IN URBAN STORMWATER MANAGEMENT

Session Chair:

Richard R. Horner, University of Washington/
King County Resource Planning Section

INTRODUCTION

Richard R. Horner[1]

The papers to be presented in this first session all derive from work done in the **Puget Sound Wetlands and Stormwater Management Research Program.** The name of this program was carefully chosen to signify:

- That it is *regional,* applying to all of Puget Sound;
- That attention is being paid to both the *wetlands* found in urban areas and the *stormwater* that affects them;
- That the intent is to obtain the knowledge needed to improve the *management* of both; and
- And that this shall be done by conducting *research* through the application of an experimental design according to the scientific method.

The stimulus for the research program was the understanding that urban growth changes both the quantity and quality of stormwater runoff. This recognition brought with it the idea among stormwater managers that wetlands could be put to use to manage increased urban runoff quantities, due to their ability to store runoff and to attenuate high stream flows. It was also known that wetlands can capture pollutants, thus improving runoff water quality as well.

When resource managers asked whether the use of these wetland functions would impair others, the inability to answer that question from existing information led to the Wetlands and Stormwater Research Program.

The wetlands under study in the research program are in the west-central portions of the counties on the east side of Puget Sound, for the most part, where development is very rapid. Mostly they are palustrine wetlands in isolated depressions and headwater areas. They typically have herbaceous emergent vegetation and a water pool or channels. They also frequently have woody shrub zones and many have a forested fringe or forested pockets within. Most have a combination of water and vegetation zones.

The research program that we designed to investigate urban stormwater effects on wetlands has the following components:

- A county-wide wetlands survey undertaken in 1987
- Stormwater impact studies, begun in 1988 and designed to continue through the mid 1990s

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- A water quality improvement study, conducted from 1988-1990
- On-going laboratory and special field studies

The core of the program has been the stormwater impact component. These studies have covered five areas (hydrology, water quality, soils, plants, and animals), the first four of which will be covered in the first two papers of this session.

The study program is based on before and after urbanization and control/ treatment designs, control wetlands being those that are not undergoing significant, current urbanization. The program is being carried out in 22 wetlands, 20 in King County and 2 in Snohomish County, and it is designed to produce not only scientific understanding but management information and tools as well. Both of these products are now available in preliminary forms, and they will be expanded and refined in the future.

After the two papers generated by the Research Program we will have a change of pace. The next three papers were all generated, not entirely by coincidence I think, within the King County Surface Water Management Division and they concern aspects of basin planning. The third paper [Moorehead] I would characterize as analysis of watershed change, and so I think you will find some carry over from our previous subjects. The fourth paper [Thomas] goes on to analyze solutions to problems produced by change in an objective manner. And the final paper [Barker] then is a detailed assessment of one widely-used solution as it is currently applied.

URBAN STORMWATER IMPACTS ON THE HYDROLOGY AND WATER QUALITY OF PALUSTRINE WETLANDS IN THE PUGET SOUND REGION

Lorin E. Reinelt[1] *and Richard R. Horner*[2]

INTRODUCTION

Wetlands have received increased attention in recent years as a result of continuing wetland losses and impacts, and the realization that wetlands have many important functions and values. Wetlands are recognized as biologically productive ecosystems offering extensive, high-quality habitat for a diverse array of terrestrial and aquatic species, as well as multiple beneficial uses for humans, including flood control, groundwater recharge and water quality treatment. However, as urbanization of natural landscapes occurs, some or all of the functions and values of wetlands may be affected. Some wetlands may be impacted by direct activities such as dredging, filling, draining or outlet modification, while others may be affected by secondary impacts, including increased or decreased quantity and reduced quality of inflow water.

Wetlands in Urbanizing Areas

In urbanizing areas, the quantity and quality of stormwater can change significantly as a result of developments in a watershed. Increases in the quantity of stormwater may result from removal of trees and other vegetation, new impervious surfaces (e.g., roads, buildings) and installation of storm sewer piping systems. On the other hand, decreased inflow of water can result from modifications in surface and groundwater flows. The quality of stormwater may decrease due to construction activities, increased automobile traffic, application of fertilizers and pesticides, and domestic animal wastes. For cases where wetlands are the primary receiving water for urban stormwater from new developments, it is hypothesized that the effects of watershed changes will be manifested through changes in hydrology and water quality.

Puget Sound Wetlands and Stormwater Management Research Program

This paper presents results from the hydrology and water quality components of a study examining the long-term effects of urban stormwater on wetlands (part of the Puget Sound Wetlands and Stormwater Management Research

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Program). The complete study also includes the examination of soils, plants and animals (King County Resource Planning, 1987). The objective of the study is to determine the types, degrees, rates, and significance of ecological change, if any, that accompany discharge of urban stormwater to freshwater palustrine wetlands. This information is being used to determine how negative impacts can best be avoided or minimized.

Results are presented for 19 wetlands in King County for data collected between April 1988 (start of study) and November 1990. The wetlands were chosen primarily based on wetland size, plant communities and known plans for development in the watersheds of half the wetlands. The wetlands with known plans for watershed development were paired with similar wetlands expected to experience no new development. The study is designed to examine change over a five to seven year period.

METHODS AND MATERIALS

A detailed description of the methods and materials for this study was presented in Reinelt and Horner (1990). The following section represents a summary.

Wetland Hydrology

Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes (Mitsch and Gosselink, 1986). Water depth, flow patterns, and duration and frequency of flooding influence the biochemistry of the soils and are major factors in the selection of wetland biota. Precipitation, surface water inflow and outflow, groundwater exchange and evapotranspiration are the general factors that influence wetland hydrology. Specific factors, including wetland-to-watershed area ratios, level of watershed development, wetland morphometry, outlet conditions, and soils, however, often determine water level fluctuation (WLF). WLF is perhaps the best single indicator of wetland hydrology, because it integrates most of the above factors.

In this study, wetland water levels were measured approximately eight times a year both instantaneously (using a staff gage) and as a maximum since the preceding site visit (using a crest-stage gage). WLF was defined as the difference between crest and instantaneous gage readings. WLF was expressed for each wetland as a mean (average of values for all reading occasions) and a maximum (for the full study period). Two types of hydrologic systems were distinguished for purposes of the data analysis: open-water (OW) and flow-through (FT). The OW systems contain significant pooled areas and possess little or no flow gradient, while the FT systems are often channelized and possess a significant flow gradient.

Daily precipitation data from stations nearest to the study wetlands were obtained from King County Surface Water Management Division. Water-year precipitation totals from 1988 to 1990 and seasonal distributions contribute to the hydrologic picture of the wetlands.

Wetland Water Quality

Fourteen wetlands were sampled during 1988 and five more were added in 1989. Water samples were collected on approximately eight occasions per year. Sampling was stratified so that more samples were collected during the wet (November-February) and dry (July-September) seasons and fewer samples were collected during the transition seasons. On some occasions during the summer, between one and nine wetlands were completely dry; thus, no water samples were collected then at those wetlands. Sampling consisted of grab samples taken at the first location possible in the following hierarchy (open water, outlet, downstream of inlet). Samples were analyzed for the following variables:

1) Conventionals: temperature, dissolved oxygen (DO), pH, conductivity, alkalinity, total suspended solids (TSS);
2) Nutrients: ammonia- (NH_3-N) and nitrate+nitrite- (NO_3+NO_2-N) nitrogen, soluble reactive (SRP) and total phosphorus (TP);
3) Biological: chlorophyll a, phaeophytin a, fecal coliforms (FC), enterococci;
4) Metals: cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn).

The water quality data were grouped in a variety of different ways to perform statistical analyses and examine trends. The data were grouped by occasion (e.g., each occasion, each season, all occasions), by each or all wetlands, and by categories (e.g., control versus treatment, OW versus FT system, pre-existing level of watershed urbanization).

Expected change in watersheds, in terms of new development, was the basis for differentiating control (C) sites (i.e., no change or development expected to occur in the wetland watershed) from treatment (T) sites (i.e., change or development expected to occur in the wetland watershed). The following three categories were established to distinguish pre-existing watershed conditions in terms of percent coverage:

1) Nonurbanized (N): less than 10 percent urban land uses
2) Moderately urbanized (M): 10 to 40 percent urban land uses
3) Highly urbanized (H): greater than 40 percent urban land uses

Combining the treatment status and level of watershed urbanization yielded five categories: CN, CM, CH, TN, TM. No wetlands fit a treatment/highly urbanized category, thus far.

Seasons were determined based on literature guidance and expert judgment relative to expected plant uptake or release of dissolved substances in the Pacific Northwest. For the period of study, the following five seasons, dates, and classifications were used:

Season 1 (03/01 - 05/15): early growing (some uptake expected);

Season 2 (05/16 - 08/15): intermediate (high uptake expected);

Season 3 (08/16 - 09/30): decline (gradual release expected);

Season 4 (10/01 - 11/15): decay (high release expected);

Season 5 (11/16 - 02/28): dormant (continued release expected).

The Student's t-test was used in the analysis of hydrologic and water quality data to compare the difference between two population means (e.g., T vs. C wetlands, OW vs. FT systems). The test assumes that both populations possess a normal probability distribution and that their variances are equal. A pooled estimator of the variance is used in the t-test to pool the information from both samples.

RESULTS AND DISCUSSION

Summary information for all wetlands, including classifications for the different categories noted above and hydrologic statistical data, is shown in Table 1. The following section highlights the most significant results. Further results for 1988 and 1989 were reported in Reinelt and Horner (1990). All references to statistical significance are for $\alpha = 0.05$, unless otherwise noted.

Table 1
***WETLAND PHYSICAL AND HYDROLOGIC SUMMARY INFORMATION** (sorted by mean occasion water level fluctuation). (a)*

Wetland Name	Acronym	Outlet Condition	WLF	Dry in Summer?	OW/FT	Sampling Location	C/T	N/M/H	Inst. (m)	Crest (m)	Mean Occasion WLF (m)	Study Maximum WLF (m)
Ames Lake 3	AL3	None	FL	Y	OW	OW	C*	N	0.17	0.30	0.04	0.62
Middle Green River 36	MGR36	Bulkhead	SL	N	FT	Out	C	N	0.22	0.28	0.06	0.21
Jenkins Creek 28	JC28	Int. Stream	SL	Y	FT	FW	T	M	0.07	0.14	0.06	0.25
Raging River 5	RR5	Beaver Dam	FL	N	OW	OW	C	N	0.33	0.47	0.08	0.50
Soos Creek 4	SC4	Culvert	SL	Y	FT	Out	C	M	0.09	0.21	0.09	0.30
Snoqualmie River 24	SR24	Road	FL	N	OW	OW	C*	N	0.37	0.53	0.12	0.67
Klahanie East	KE	None	FL	Y	OW	OW	T	N	0.08	0.28	0.13	0.42
East Lake Sammamish 61	ELS61	Int. Stream	FL	N	OW	OW	T	M	0.41	0.57	0.14	0.72
Big Bear Creek 24	BBC24	Beaver Dam	SL	N	OW	OW	C*	M	0.39	0.53	0.14	0.25
Patterson Creek 12	PC12	Beaver Dam	FL	N	OW	OW	T	N	0.41	0.55	0.15	1.00
Soos Creek 84	SC84	Int. Stream	FL	Y	OW	OW	T	M	0.40	0.67	0.20	1.08
East Lake Washington 1	ELW1	Lake	SH	N	FT	FW	T	M	0.14	0.35	0.21	0.66
Forbes Creek 1 (b)	FC1	Beaver Dam	S/FH	N	FT	OW	C	H	0.41	0.62	0.22	0.89
Tuck Creek 13	TC13	Culvert	FL	Y	OW	OW	T	N	0.22	0.49	0.22	0.75
Harris Creek 13	HC13	Beaver Dam	FL	N	OW	OW	C	N	0.72	0.97	0.22	1.47
Lower Cedar River 93	LCR93	None	FH	Y	FT	FW	C	M	0.18	0.44	0.22	0.80
East Lake Sammamish 39	ELS39	Culvert	FH	Y	OW	OW	T	M	0.17	0.66	0.37	1.61
Lower Puget Sound 9	LPS9	Drain inlet	FH	Y	FT	FW	C*	M	0.21	0.74	0.43	1.72
Bellevue 31	B31	Culvert	SH	N	FT	Out	C	H	0.67	1.17	0.49	1.33

(a) See text for explanation of acronyms/abbreviations
(b) Periodic removal/construction of beaver dam has resulted in stable and fluctuating base water levels

Wetland Hydrology

The mean instantaneous and crest water levels at the gages are given in Table 1. Also given are the mean occasion and maximum study-period WLFs. Water depth and WLF varied widely for the 19 wetlands. Mean instantaneous water depths varied from 0.07 to 0.72 m; mean crest depths varied from 0.14 to 1.17 m. The mean occasion and maximum study-period WLFs are shown in Figure 1.

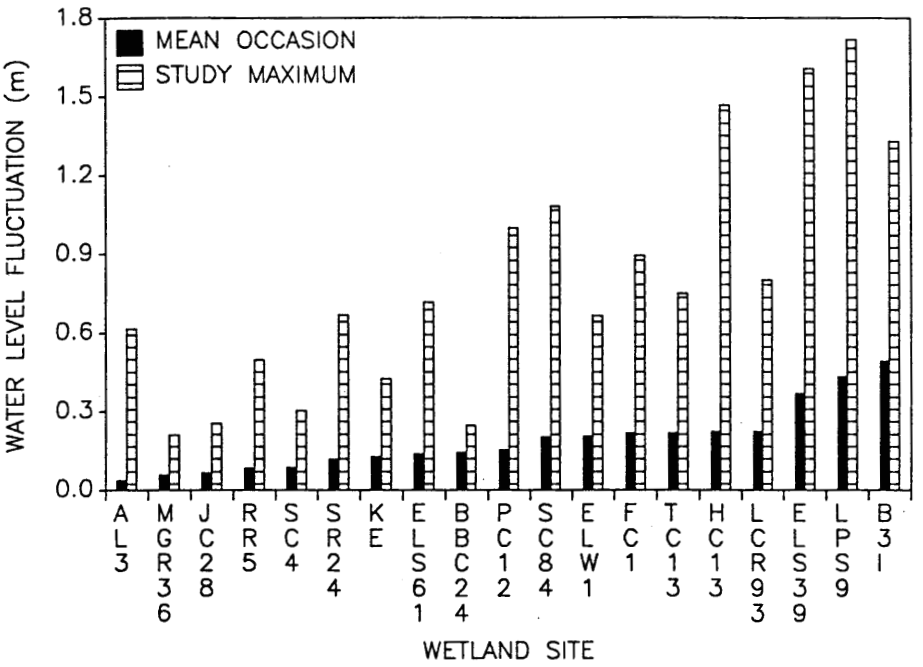

Figure 1.
MEAN OCCASION AND MAXIMUM STUDY-PERIOD WATER LEVEL FLUCTUATION.

The WLF for the 19 wetlands generally fit into one of four basic patterns: (1) stable base water level with low event fluctuations (SL), (2) stable base water level with high event fluctuations (SH), (3) fluctuating base water level with low event fluctuations (FL), and (4) fluctuating base water level with high event fluctuations (FH). Change over the study period was the basis for defining base water levels (stable as less than or equal to 0.20 m; fluctuating as greater than 0.20 m) and event fluctuations (low as less than or equal to 0.20 m; high as greater than 0.20 m) Examples of the four patterns are shown in Figure 2.

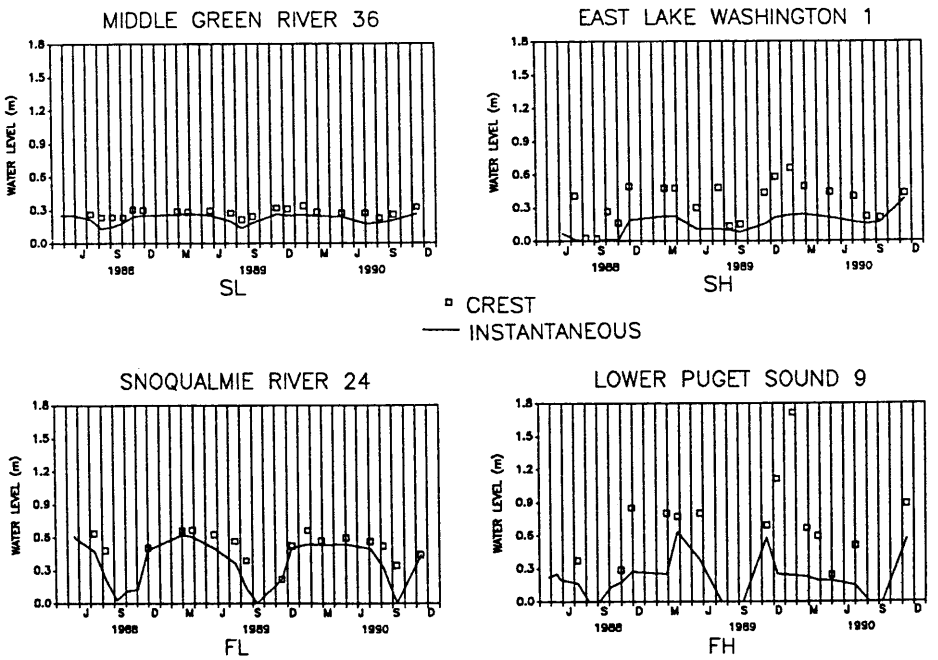

Figure 2.
EXAMPLES OF THE FOUR PATTERNS OF WATER LEVEL FLUCTUATION.

The level of watershed urbanization and wetland outlet conditions appear to be the most important factors influencing water level fluctuation. The three wetlands with the highest WLFs (B3I, LPS9, ELS39) have highly or moderately urbanized watersheds and constricted outlets (e.g., culvert, drain inlet) (Figure 1, Table 1). Five of the seven wetlands with the lowest WLFs have non-urbanized watersheds (two are moderately urbanized). The type of wetland hydrologic system (OW, FT) was not a significant factor in determining WLF. Wetland-to-watershed ratios as a factor affecting WLF will be examined in the near future.

Twelve-month precipitation totals for water years 1988 through 1990 (October-September) showed considerable variation both spatially (around King County) and temporally (between years). For these three years, between 60 and 75 percent of the annual precipitation fell during the wet season (October-March). Mean annual precipitation totals varied from 1033 to 1289 mm, with minimum and maximum values of 844 and 1602 mm, respectively.

Wetland Water Quality

Overall, the water quality of the wetlands was characteristic of that found in freshwater lakes and streams in the region. The water quality data were highly variable between wetlands and occasions, but some general trends emerged from the first two and one-half years of the study.

The CH wetlands had the highest mean values among the five categories for temperature, DO, pH, conductivity, alkalinity and TSS; FC and enterococci geometric mean (GM) values were also highest. The TM wetlands were second highest for the same variables (except temperature) and highest for chl a and NO_3+NO_2-N. Mean conductivity, alkalinity and TSS, and GM of the bacteria (FC, enterococci) exhibited the greatest differences between the wetlands with the higher level of watershed development (CH and TM), as compared with the other three categories (CN, CM and TN). Thus, these variables are probably the best indicators of degraded water quality conditions associated with urbanization.

Comparisons of the wetlands by hydrologic system (OW, FT) were carried out to determine if there were differences between water quality variables due to factors such as light exposure, water exchange and residence time. Conductivity, pH, alkalinity, phaeophytin a, NO_3+NO_2-N, FC and enterococci were significantly different between OW and FT systems. Alkalinity and pH values were lower in the OW systems, largely resulting from the influence of three wetlands with pH below 6.0 and alkalinities below 6 mg/L. Conductivity was much higher in the FT systems because of the high level of urbanization in the watersheds of several wetlands in this category.

Chlorophyll a (significant at $\alpha = 0.10$) and phaeophytin *a*, indicators of algal growth, were higher in the OW systems, probably as a result of greater light exposure and longer residence times. Higher bacteria levels in the FT systems likely resulted from the greater urbanization of those wetland watersheds and the quiescent nature of OW systems, which allows sediment particles and associated bacteria to settle out.

The treatment status of the wetlands is expected to play a more important role in the study in the long term. Change (as opposed to absolute values) of the given variables will be compared to see if significant differences occur. In the initial analysis, only three variables (SRP, conductivity and NO_3+NO_2-N) emerged as significantly higher in the treatment wetlands on several occasions or seasons. All three often increase as a result of watershed development and reflect higher loadings of nutrients and dissolved salts.

Total and dissolved metal concentrations were measured in all wetlands on four occasions during 1988. Dissolved metal concentrations were mostly

below detectable levels and thus were dropped from the 1989 and 1990 analyses. Generally, total metal concentrations were quite low for all four metals. The following data were obtained from the 125 samples analyzed for total metals between 1988 and 1990 that had detectable levels (range, n, median):

Cd - 0.6 to 4.0 µg/L, n = 5, median = 0.7 µg/L;

Cu - 5 to 15 µg/L, n = 19, median = 7 µg/L;

Pb - 5 to 22 µg/L, n = 18, median = 8 µg/L;

Zn - 8 to 120 µg/L, n = 55, median = 18 µg/L.

All wetlands had metals above detectable levels in two or more samples. The greatest number of samples with detectable metals occurred in wetlands LPS9 (n = 10) and B3I (n = 9). It is important to note that most of the samples were taken within the wetlands and not during storms. Results from a companion study of wetlands B3I and PC12 focusing on storm sampling at the inlet and outlet, showed much higher metal concentrations.

Water quality data are often compared with criteria for purposes of assessing the conditions of the waters in question. Criteria may take the form of regulatory standards or generally accepted values derived from research literature. For purposes of comparison in the following analysis, informal criteria also were established based on the authors' experience and judgment and how the data were grouped. The criteria and study results for selected variables are given in Table 2. These criteria are mostly for freshwater streams, but similar criteria may be adopted for wetlands.

Mean DO values in nine of the 19 wetlands were below 6 mg/L. Generally, the OW wetlands had lower DO values. Increased TSS concentrations in wetlands are usually related to storm events in urbanized areas and construction activities. It is worth noting that none of the non-urbanized wetlands had mean TSS values over 10 mg/L. Summer chlorophyll a and winter TP provide a perspective on eutrophication. [Note: eutrophication of wetlands, generally unlike lakes, is not necessarily a result of disturbance.] Chlorophyll a mean values above 10 µg/L were found most often in OW systems, where residence times are lower and light exposure is greatest. CN and CM wetlands were the only ones with TP levels below 20 µg/L, and FT wetlands most commonly had TP levels above 50 µg/L.

Three wetlands had GM values for FC above 200 organisms/100mL; two of these were in the CH category. These values exceed the water quality criteria for surface waters of Washington State for Class AA, A, and B waters. Finally, over half the wetlands contained Pb concentrations above the criterion on at least one occasion. However, there was no apparent association between Pb levels and urbanization.

Table 2.
***CRITERIA COMPARISON FOR SELECTED VARIABLES** (all occasions/each wetland). (a)*

Variable	CV (b)	Range	Criteria (c)	CN	CM	CH	TN	TM	C	T	OW	FT	All
DO (mg/L)	0.40	1.1-8.4	<6	4	2	0	2	2	6	4	7	3	10
			>6	1	2	2	1	3	5	4	4	5	9
Cond. (umhos/cm)	0.61	24-215	<100	4	3	0	3	1	7	4	9	2	11
			100-200	1	1	0	0	3	2	3	2	3	5
			>200	0	0	2	0	1	2	1	0	3	3
TSS (mg/L)	0.68	1.3-15.1	<10	5	4	1	3	4	10	7	10	7	17
			>10	0	0	1	0	1	1	1	1	1	2
Summer Chl a (µg/L) (late May-Sep)	1.54	1.3-96.9	<10	4	3	2	1	1	9	2	5	6	11
			>10	1	1	0	2	4	2	6	6	2	8
Winter TP (µg/L) (Oct-Mar)	0.71	14-129	<20	2	2	0	1	0	4	1	3	2	5
			20-50	2	0	0	1	4	2	5	3	4	7
			>50	1	2	2	1	1	5	2	5	2	7
Fecal Col. (#/100mL)	0.68	1-250	<50	4	4	0	3	4	8	7	11	4	15
			100-200	1	0	0	0	0	1	0	0	1	1
			>200	0	0	2	0	1	2	1	0	3	3
Total Lead (µg/L) (d)	0.53	5-22	<3.2	2	1	1	3	1	4	4	7	1	8
			>3.2	3	3	1	0	4	7	4	4	7	11

(a) Values are arithmetic means, except FC (geometric mean) and Pb (values above detectable levels)
(b) CV = Coefficient of variation = standard deviation/mean
(c) Sources: Welch (1980), Chapter 173-201 WAC, U.S. EPA (1986)
(d) Criteria is for four-day average concentration for hardness = 100 mg/L as CaCO3.

CONCLUSIONS

The quantity and quality of stormwater entering many palustrine wetlands in the Puget Sound region has changed as a result of rapid development in urbanizing areas. The purpose of this paper has been to characterize the hydrology and water quality of palustrine wetlands affected by urban stormwater, in comparison to unaffected systems. This information, then, may help to explain observed changes in wetland soils, plants and animals over time. Additionally, if observed effects of stormwater on wetlands can be documented, it may be possible to mitigate these effects through watershed controls or pretreatment efforts.

The hydrology of the wetlands as measured by WLF was highly variable. Differences in WLF were attributed to level of watershed development and outlet conditions in the wetlands. The CH and TM wetlands exhibited the most degraded water quality conditions. In particular, the higher values for conductivity, TSS, and bacteria for these two wetland categories reflect degraded water quality conditions associated with urbanization. Plant and animal communities, however, are likely to be affected more by fluctuations in water level than by pollutants at the levels generally found in runoff from urbanizing areas.

Overall, the water quality of the wetlands was characteristic of freshwater systems receiving stormwater inputs. The values observed were similar to those found in freshwater lakes and streams in the region. Since water is transient, its greatest effect probably results from accumulation of pollutants in the sediments due to physical settling and chemical reactions. High fluctuations in water levels likely pose more significant problems to wetland functions because of potential effects on plant succession, habitat and breeding conditions.

ACKNOWLEDGEMENTS

This research was partially supported through grants from the State of Washington Conservation Commission and the Washington State Department of Ecology through the Centennial Clean Water Fund. We gratefully acknowledge the support and efforts of the King County Conservation District, King County Parks, Planning and Resources Department (Resource Planning Section), and the Municipality of Metropolitan Seattle.

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THE EFFECTS OF URBAN STORMWATER ON WETLAND VEGETATION AND SOILS — A LONG-TERM ECOSYSTEM MONITORING STUDY

Sarah S. Cooke[1]

INTRODUCTION

The Puget Sound Wetlands and Stormwater Management Research Program initiated in 1986 by King County consists of ecological monitoring of 19 wetlands in the Puget Trough region in order to investigate the long-term consequences of stormwater runoff quantity and quality changes on wetlands ecosystems. The objectives are to identify components of the ecosystem that are obviously effected by stormwater inputs. Monitoring focuses on those components expected to reflect cumulative burden, rather than relatively transient phenomena. Each study provides a unique data base that offers the opportunity to determine statistically significant differences between two groups of wetlands: those treatment sites affected by new development activity and subsequent urban drainage, and those control sites that will not receive such effects.

The work discussed in this paper represents: (1) characterization of soils and vegetation communities in a set of King County palustrine wetlands that historically were subjected to differing amounts of urban influence in their watersheds; (2) determination the degree to which urban stormwater affects wetlands vegetation composition, cover, and productivity, and the rate at which changes in these vegetation characteristics occur, given a measured change in water quantity or quality; (3) preliminary findings on the degree and rate of heavy metals uptake and accumulation by common wetlands plant species as a result of the receipt of urban stormwater and, in addition, how this relates to heavy metal accumulation in the wetland soils; and (4) an up-to-date understanding of the mechanisms causing change in wetlands plant communities subjected to urban stormwater, especially the roles of hydrologic modification and the degradation of water quality.

METHODS AND MATERIALS

Detailed protocol descriptions for the project can be found in Cooke et al. (1989a), and Cooke and Conolly (1990).

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Two transects were established in each wetland perpendicular to the flow of the wetland. Permanent stations were established along each line every 15 meters, so that measurements could be recorded in the same location in successive years. Measurements of vegetation percent cover and species composition, plant productivity and soil samples were taken at these stations which represented either transitional communities or homogeneous communities. This method of sampling makes it possible to determine direct correlations between soil chemistry and physical properties, and the vegetation.

Plant abundances were examined by the classification and ordination methods routinely used for plant community analyses, TWINSPAN (Hill, 1979b) and DECORANA (Hill, 1979a). TWINSPAN analyses are used to identify different plant communities based partially on the presence or absence of indicator species. These communities correspond to specific stations along the transect lines in individual wetlands. DECORANA graphics are plotted on two-dimensional plots, where similar vegetation communities (wetland stations) are located near each other, and dissimilar vegetation communities are far apart.

The most common method of determining the productivity of a habitat is by assessing above-ground vegetative biomass, or standing crop (Moore and Chapman, 1986). This is a measurement of the weight of organic matter assimilated by an organism or community per unit area present at a given instant of time. There are a few methodologies listed in the literature for sampling shrub and tree biomass, but none appear to give consistent results on a long-term basis (Moore and Chapman, 1986; Milner and Hughes, 1968). Accordingly, it was decided to sample only the above-ground emergent vegetation. The protocol for biomass measurement follows that of Cox (1982) and Wiegert (1962)

Foliar analyses for the heavy metals arsenic, cadmium, copper, lead, and zinc were performed on tissue samples collected in all wetlands on various species. The species included; cattail (*Typha latifolia*), reed canarygrass (*Phalaris arundinacea*), hard hack spirea (*Spirea douglasii*), soft rush (*Juncus effusus*), broadleaf pondweed (*Potamageton natans*), small fruited bulrush (*Scirpus microcarpus*), water parsley (*Oenanthe sarmentosa*), and simplestem burreed (*Sparganium emersum*).

Soil samples were taken with a 5 cm diameter PVC pipe to 15 cm depth. The samples were described for pH, redox, color, particle size, total nitrogen, total phosphorous, heavy metals content, and organic content.

RESULTS

Vegetation Community Characterization and Changes Seen After New Inputs of Urban Stormwater

The vegetation communities described by the DECORANA analysis are much the same as some of those identified by Kunze (1987). Changes in the spatial distribution of a vegetation station on the DECORANA plot from one year to the next indicate that some component of the vegetation, either the species composition, the percent cover, or both, has occurred. In Figure 1a, the plot of the control wetland sites (where the regions surrounding the wetlands have remained the same in a human-impact sense) shows that in undisturbed wetlands there is very little spatial change and, consequently, change in vegetation. This is not true for the treatment wetlands displayed in Figure 1b, however, where it is obvious that for a few of the wetland stations, (and consequently the wetlands), changes were seen in the species present and/or the percent cover after treatment.

When identifying vegetation diversity in the Puget Trough, it was of interest to examine both the total numbers of species found throughout the region, and how often each species appeared in individual wetlands. There were 153 species of vascular and moss plants found among the 19 study sites. The majority of wetlands contain less than 25% of the total wetland species found. Some species occur in only one or two of the study wetlands. This indicates that, converse to popular thought, each wetland is uniquely diverse.

Vegetation Productivity Characterization and Changes Seen After New Inputs of Urban Stormwater

Productivity is defined as the amount of plant tissue produced per unit area (measured here as dry, above ground tissue). Productivity values in the study sites range from a low of 29.5 g/m^2, to 298 g/m^2.

There appears to be no direct pattern of productivity that correlates with the degree of urbanization that a wetland has experienced. Indirectly however, the more urbanized a wetland, the more likely it is that the emergent meadows will be a monoculture of reed canarygrass (*Phalaris arundinaceae*) or cattail (*Typha latifolia*). Productivity is related to the particular species sampled. There is also a correlation with the species diversity of a wetland and the productivity of the wetland. The productivity values were consistently higher in those wetlands that contained only one or two species, compared to those that contained three or more species.

Soft rush (*Juncus effusus*) is present only in sites displaying low productivity. Sedges (*Carex* spp.) are often present in highly productive sites, while mannagrasses (*Glyceria* spp.) are often present in low to medium productive

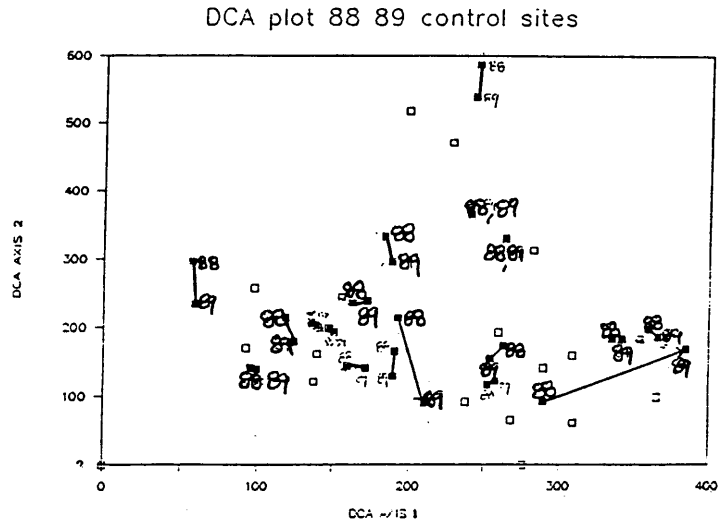

Figure 1A

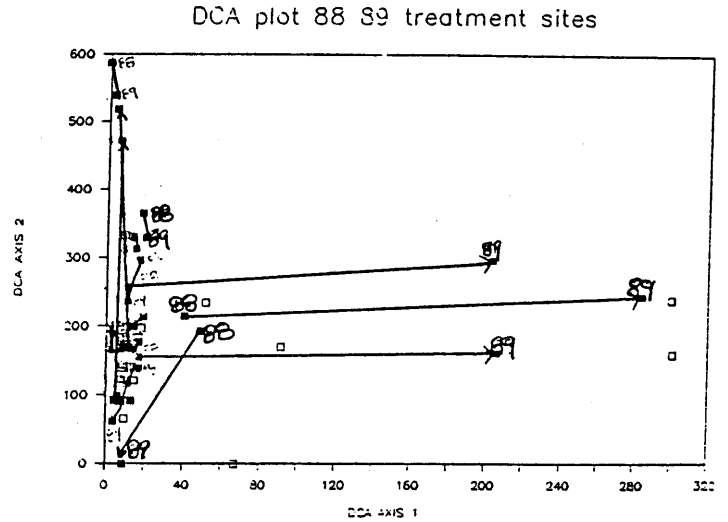

Figure 1B

sites. Cattail can be found in low and highly productive sites. Bracken fern (*Pteridium aquilinum*), an example of an invasive species common to highly disturbed sites, is associated with some of the highest productive sites. The native rushes (*Juncus* spp.) and hard hack spirea (*Spirea douglasii*), horsetail (*Equisetum* spp.), creeping buttercup (*Ranunculus repens*), and most grass species tend to be found only in the sites with low productivity. Reed canarygrass is present in low, medium and highly productive sites.

Wetland Vegetation Heavy Metals Contents, Native plant abilities to Sequester Heavy Metals, and Changes in Foliar Contents As They Reflect Stormwater Inputs

Foliar heavy metal contents for lead (Pb) and Zinc (Zn) in Pacific Northwest wetlands which have experienced no urbanization, moderate urbanization, and heavy urbanization can be seen in Figures 2a and 2b. Foliar tissue levels are compared to soil metal concentrations from samples taken adjacent to the plants. In general, metal contents were below detection limits of the analytical equipment. Zn was high in a few of the urbanized wetlands in terms of levels quoted for wetlands in other regions of the world (Lehtonen, 1989; Shierup et al., 1981; Hutchinson et al., 1975) One of the control non-urbanized wetlands displayed moderately high levels of Cadmium (Cd) and Zn. High levels of Pb and Zn are occurring irrespective of the degree to which urbanization has occurred.

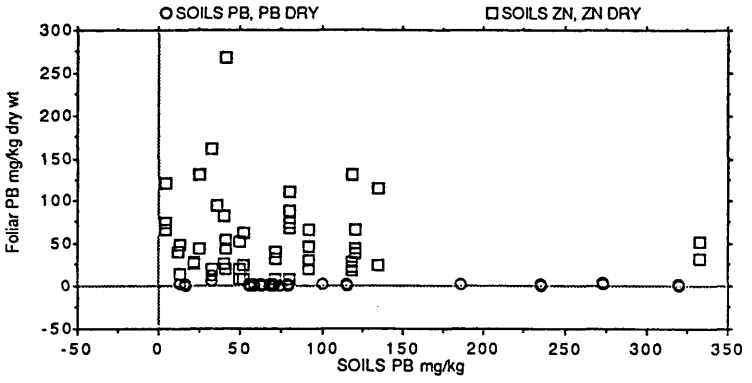

Figure 2A

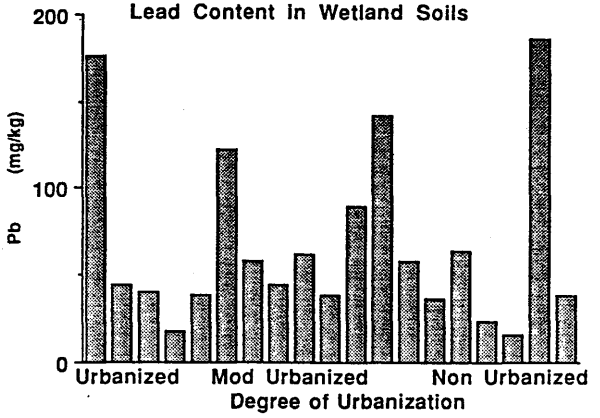

Figure 2B

Preliminary data on local plant species success at sequestering heavy metals can also be garnered from the study. Table 1 lists the species studied and their ability to sequester each of the heavy metals monitored. In general, foliar heavy metals concentrations are typically higher in aquatic plants than species not adapted to growing in water. Hardhack spirea and water parsley appear to be the best plants to sample if you want to monitor many different metal concentrations in one species.

Table 1:
COMMON NORTHWEST WETLAND PLANT SPECIES — SUCCESS AT SEQUESTERING HEAVY METALS.

	Heavy Metal				
Species	As	Cd	Cu	Pb	Zn
Oenanthe sarmentosa	x		x	x	x
Sparganium emersum	x				
Potamogeton natans	x				
Scirpus microcarpus	x			x	
Typha latifolia	x		x		
Spirea douglasii		x	x	x	x
Ranunculus repens			x		x
Phalaris arundinaceae			x		

Hydrologic and Water Quality Tolerances of the Native Vegetation in Puget Trough Wetlands

Table 2 lists some common plants and their tolerances to different hydrologic regimes. It appears invasive species such as reed canarygrass, hardhack spirea, and soft rush are so successful because that they have broad ecological tolerances and are not only able to live in many different habitats, but are also able to tolerate changes in hydrologic regime and water quality better than many native species.

Species richness is affected by increases in water level fluctuation. Wetlands with mean annual water fluctuations of less than .6 ft tend to display lower species richness than wetlands with less fluctuations (Azous, 1990).

Soil Survey Results

Most of the wetlands contained, at a minimum, some pockets of peat soils of primarily sedge/grass origin. pH values were acidic for all the wetlands. The pH readings tended to be less acidic in the inundated soils (mean pH of 6.5), and more acidic in the soils that were drained for part of the year (mean of 5.5). Total nitrogen and phosphorous concentrations were highest in soils from urbanized wetlands, especially in those whose water samples also showed the highest levels of these elements. Siltation is occurring in most of the treatment but none of the control wetlands.

Table 2.
HYDROLOGY PLANT ASSOCIATIONS.

Species	DT	EI	IT
Phalaris arundinaceae	yes	yes	yes
Spirea douglasii	yes	yes	yes
Juncus effusus	yes	yes	yes
Juncus species (except *J. effusus*)	no	no	no
Carex species	Each *Carex* species is very specialized in tolerance to duration, depth and early season inundation		

DT = Drought tolerance, especially middle to late season
EI = Early growing season inundation tolerance
IT = Tolerance to any depth of short-term inundation

Soil heavy metal concentrations for Pb and Zn are displayed in Figures 2a, and 2b. In general, metal levels were higher in the urbanized sites, but not consistently so. As an example, the highest lead levels were found in a totally non-urbanized wetland site.

DISCUSSION

The implication of decreased species richness associated with higher water level fluctuations than are found in natural systems is that urbanization is affecting the diversity of Puget lowland wetland communities. This is of particular concern when viewed in the context of regional wetland diversity. It is also important to understand that plant species in the region are sparsely distributed and that loss of an individual wetland could significantly affect regional plant diversity (Azous, 1990).

High levels of heavy metals are occurring in water and sediments in Puget Lowland wetlands whether urbanization has occurred or not. This indicates a necessity for monitoring all wetlands for heavy metals and not assuming that because a watershed is still relatively pristine, metals are not a water quality or sediment problem (Azous, 1990).

Soils are storage facilities for many potentially toxic compounds: heavy metals, organics, and bacteria. Changes in the pH or redox potential due to urban stormwater inputs can render many of these toxins available from the storage pool where they can have an immediate effect on wetland soils and plants, both in-situ and potentially downstream. Soils are therefore a very useful tool for monitoring chemical and physical changes in wetland ecosystems.

ACKNOWLEDGEMENTS

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MANAGING URBAN GROWTH AND AQUATIC HABITAT IN A RAPIDLY URBANIZING BASIN

Margaret Moorehead, Bruce L. Barker, Derek B. Booth, Ph.D., Robert R. Fuerstenberg, and Richard E. Thomas, P.E.[1]

IMPACTS OF URBAN GROWTH ON STREAM SYSTEMS

The Soos Creek basin is a 70-square-mile watershed in south King County, Washington. Much of the basin is rural and the streams there are in good or excellent condition. As a result, these stream reaches have few flooding and water pollution problems and have some of the best salmonid habitat in western King County. But elsewhere in the basin, high-density development has occurred and the streams display many of the unintended problems associated with that growth activity. These problems include flooding, erosion and sedimentation, water pollution, and degradation of valuable aquatic habitat.

County land-use policy designates much of the basin for high- density urban land uses (King County, 1985). A full range of analytical tools including a continuous hydrologic model was used to predict the condition of the basin after development to these projected densities. This analysis, developed as part of the Soos Creek Basin Plan (King County, 1990), predicts substantial development-related changes in surface water systems.

As the basin urbanizes, dramatic changes in hydrology will occur. Changes in the infiltration capacities of soils cause most of these changes. Under pre-development conditions, soils in many parts of the basin infiltrate even extreme precipitation events. After clearing and grading, the ability of soils to infiltrate and store water is greatly reduced. This soil disturbance, coupled with the introduction of impervious surfaces, results in post-development peak flows in many reaches that are double or triple the pre-development flows. In addition to the increased runoff for rainfall of a given magnitude, the number of runoff events increases with urbanization. For example, the average duration that the forested 10-year discharge is exceeded is approximately 40 times longer under developed conditions than under the historic forested flow regime. These changes in hydrology will impact channel stability, aquatic habitat quality, and the frequency and severity of road and house flooding at several sites.

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By analogy to existing channel dimensions and discharges, increased flows are calculated to increase channel widths and depths by up to 50 percent. Sediment transport capacities, based on simulated 2-year discharges and existing sediment sizes, are predicted to almost triple in the major streams of the basin. A threshold of significant channel erosion, recognized from existing channel conditions and basal shear stresses applied by the 2-year discharge, allows prediction of additional regions of future channel erosion. In contrast to the greatly increased intensity of future erosion, the locations of such erosion expand only modestly because most susceptible reaches have been affected already.

Development to previously planned densities in the Soos Creek basin will change aquatic habitat across the basin through time, changing the hierarchy of ecosystem structure and function. Habitats within a single system will be altered by more frequent, larger peak flow events that modify pool-riffle structure and redistribute large roughness elements such as wood. For example, floods of about the forested 5-year flow are observed to be necessary to change habitat structure by moving significant structural elements in stream channels such as large organic debris. Analysis of a neighboring drainage basin found that whereas this 5-year discharge occurred eight times in a 40-year period under forested conditions, it occurs over six times on average each year under urban land-use conditions (Booth et al., 1990).

Additional urbanization impacts to habitat are recognized from more developed drainage basins (King County, 1987; Metro, 1988) and are judged inevitable here as well. Summer low flows decrease as soil compaction and increases in impervious surfaces reduce infiltration of rainfall to groundwater. Increases in erosion-causing stream flows cause changes in channel shape and increases in width-to-depth ratios. Nonpoint pollution from the more intense land uses will reduce the use of streams for recreation, agricultural and fish hatchery water supplies, and salmonid habitat. As more people live adjacent to streams, harmful activities such as dumping of trash into streams, driving of off-road vehicles through streams, and harassment of spawning fish increases.

As these changes become more widespread, habitats between streams come to resemble each other. The diversity of within-stream and between-stream habitats will decline and the salmonids, adapted as they are to high habitat diversity and complexity, will find fewer suitable refuges. Thus species diversity and abundance should be expected to decline as the basin's streams are simplified, and populations may become too small for effective reproduction. Because the cumulative effects of basin-wide urbanization are found so far to be irreversible, the probability that streams and salmonid populations therein will adapt to changing conditions is remote.

BASIN MANAGEMENT RECOMMENDATIONS

The situation in the Soos Creek Basin exemplifies the difficulty of protecting a high-quality natural resource while simultaneously accommodating high-density urban growth. Continued use of the basin's streams by people and aquatic life depends on stable stream channels, healthy habitat, and clean water. These stream characteristics in turn depend on protection of the diverse elements and functions of the watershed. Mitigation can replace a portion of the functions lost when development occurs, but it cannot replace all functions on the scale of the 70-square mile watershed or even a small sub-basin. To protect these functions at the watershed scale, difficult choices must be made between accommodating urban growth and protecting significant aquatic resources.

The management approach also must address the diversity of surface water concerns which range from correction of existing site-specific flooding problems to prevention of nonpoint pollution throughout the basin. Thus a multi-faceted management program is recommended that emphasizes preventative basin-wide measures, but also includes site-specific projects to correct existing surface water problems.

Elements of the Management Program

Land Use Controls — Zoned densities of one unit/five acres or less are recommended over about 15,000 acres to protect significant aquatic habitat. When the King County Council adopted these controls on an interim basis in 1989, an estimated 4,500 acres were downzoned.

Regulations — Several development controls are recommended, including standards to protect undisturbed vegetated buffers of up to 150 feet adjacent to streams and wetlands; regulations that allow new development in floodplains only if no increases in flood elevations are caused; requirements to retain at least 20 percent of rural sites in undisturbed vegetation; improved drainage controls including standards that would increase the stormwater detention volume provided with new development up to 200 percent in sensitive, erosion-prone areas; and increased water quality standards for drainage facilities in areas with highly pervious soils overlying unprotected aquifers.

Enforcement and Penalties — Increased enforcement of county development codes and stronger penalties for code violations are recommended.

Education and Incentives — Education and incentive programs are recommended to encourage public participation in stream protection. These programs include a new Stream Steward position to conduct education and

citizen involvement programs, facilitate project installation, and monitor surface water management activities in the basin.

Stream Projects — Seventy-three stream improvement projects are recommended, including 12 larger scale projects to reduce flooding and instream erosion and 61 smaller projects to improve aquatic habitat and water quality. Watershed-level analysis of surface water problems and the effectiveness of stream projects allowed the 19 projects scheduled for construction prior to basin plan completion to be evaluated more thoroughly than previously possible. Only five of these previously identified projects were recommended in the plan. This management program therefore allocates public funds to projects that more effectively reduce the basin's surface water problems.

Monitoring and Plan Update — Monitoring of the basin is recommended to evaluate the long-term success of the management program in reducing surface water problems and protecting resources. This monitoring will identify changing conditions that require adjustments in basin management, including divergence from the assumptions made in the hydrologic modeling upon which much of the management program is based.

BENEFITS AND COSTS

Although significant localized flow increases will occur, the basin management program is expected to significantly reduce surface water problems such as flooding, erosion, and water pollution, and to provide substantially greater protection for the basin's valuable aquatic habitat. The basin management program will cost an estimated $5.4 million for stream improvement projects and $1.3 million for staff and start-up costs in the first year. These staff costs reduce to $480,000 in later years for on-going basin management activities.

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A COMPARISON OF BASIN STORMWATER MANAGEMENT ALTERNATIVES

Richard E. Thomas, P.E., and Jeanne Stypula, P.E. [1]

INTRODUCTION

The effects of urbanization on stream systems in the Pacific Northwest have been extensively documented (King County, 1987, 1990a, 1990b; Booth, 1990). The King County Surface Water Management Division is completing a systemwide analysis for the Hylebos Creek basin. This paper compares the costs of four management alternatives that address the effects of land-use changes in the Hylebos Creek basin.

Urbanization has increased the magnitude and frequency of storm runoff, reduced base flow, increased rates of channel erosion and degradation of water quality, and lowered diversity and abundance of aquatic life in Hylebos Creek. Public safety and welfare are threatened as a larger population is exposed to increased rates of flow and erosion. Urbanization has also dramatically affected natural resources in the basin.

Local governments respond to requests for assistance with emergency services, stricter regulations, and flood control or resource protection projects (American Public Works Association, undated). However, financial constraints often limit the available range of responses. In the Hylebos Creek analysis, reducing future peak flows to stabilize stream channels proved to be the most cost effective management alternative.

BASIN DESCRIPTION

Hylebos Creek is located in southwestern King County and northwestern Pierce County. The eighteen square mile basin (Figure 1) has east and west branches that join near the county line and flow northwest to Puget Sound. The West Branch has flatter gradients and large wetlands in contrast to the steep ravines and upland lakes of the East Branch. Most of Hylebos Creek flows over glacial till; where incised, it exposes deposits of sandier outwash. The east and west branches join and continue in a wide alluvial floodplain to Puget Sound.

Land use greatly varies throughout the basin, with the northern half of the West Branch system being more intensely developed than the southern half. Around the Panther Lake area, there is high-density single-family and multi

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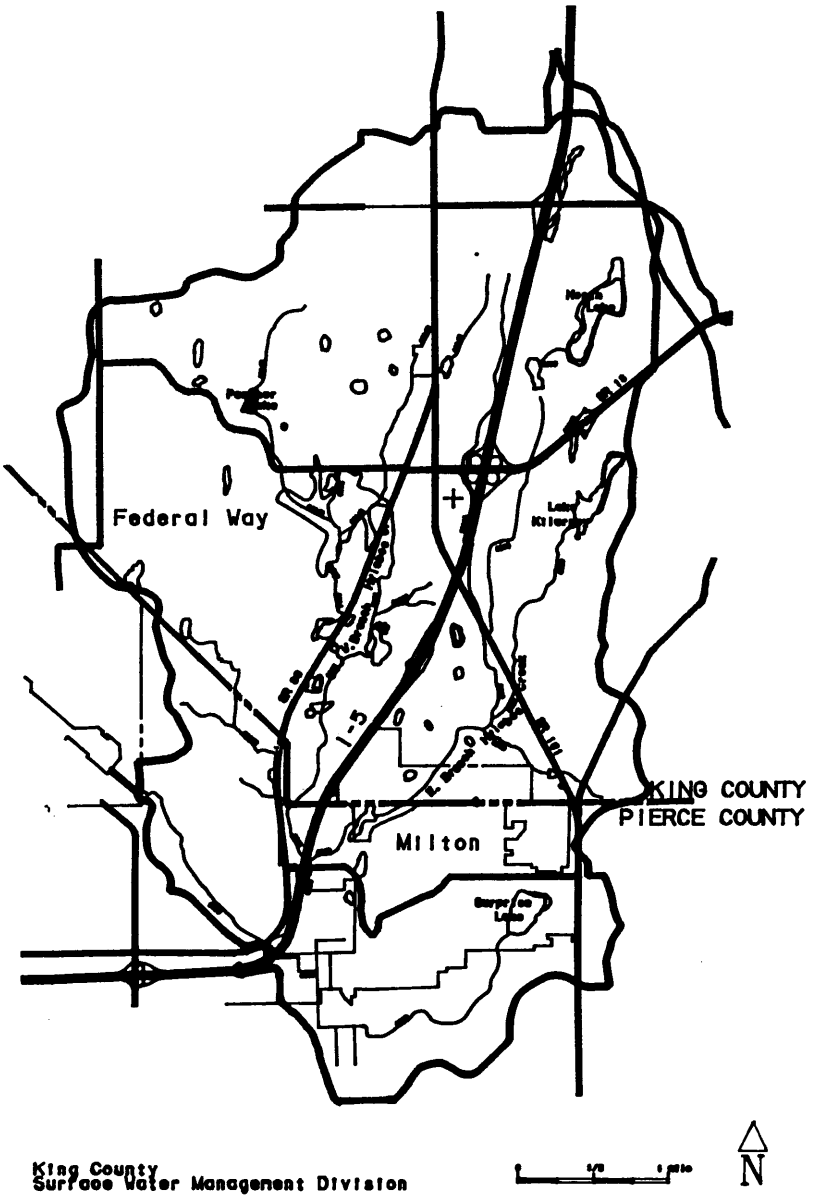

Figure 1.
HYLEBOS CREEK BASIN PLANNING AREA.

family residential and office development. The area tributary to the Spring Valley stream has commercial/industrial land uses. The upper East Branch is currently rural. Medium-density residential uses dominate in the southern portion of the East Branch system (King County, 1990c).

Several significant current and future problems have been identified for the basin (King County, 1990c). Increased flows have overwhelmed the available storage areas in the West Branch, causing flooding and erosion of downstream reaches. Turbid flood waters and urban pollutants adversely affect wetlands and areas of good quality aquatic habitat. The wetlands' ability to absorb these effects is finite, and so downstream reaches are being impacted. The East Branch also experiences flooding of residential areas and as the basin urbanizes flooding may occur in the future along SR 161.

Increased flows also result in channel downcutting and loss of aquatic habitat. The most dramatic example of channel erosion is in the East Branch ravine, where highly erodible deposits of outwash are exposed. This ravine historically supported salmonid populations and is a resource area of regional significance due to the size and quantity of large organic debris in the riparian corridor. Future channel damage is predicted to degrade much of the physical habitat. The fisheries habitat is also impacted by urban nonpoint pollutants that degrade the water quality, and by sediments that silt in the pool rearing habitat and cement spawning gravels. However even with the degradation noted, the lower portion of the Hylebos Creek system is in relatively good condition when compared to other urban basins in King County.

COMPUTER MODELING

The hydrology of this basin was simulated using the Hydrologic Simulation Program - Fortran (HSPF). HSPF is a state-of-the-art continuous model that produces streamflow estimates based on current, future, and forested land use, land cover, soil, and topographic and precipitation parameters. The Hylebos Creek model was calibrated using 1987 and 1988 streamflow and precipitation records collected by the United States Geological Service (USGS). Based on a 39-year continuous record of rainfall collected at the Seattle-Tacoma Airport station, flows were simulated for 31 subcatchments in the basin. Although "current conditions" refers to 1987 land-use, land-use has changed because of continuing development which has produced flows which exceed 1987 levels.

SOLUTIONS FORMULATION

King County has used basin plans to examine the condition of stream systems and to recommend solutions to reduce impacts of land-use changes. Prior to

1986, basin plans proposed alternative techniques to solve specific problems rather than to evaluate systemwide management alternatives. For example, the 1977 Juanita Creek Basin Plan evaluated the separate alternatives of neighborhood retention ponds, extended onsite controls, or parallel pipe systems (King County, 1977).

The current basin planning approach utilizes both capital improvements and land-use controls to manage surface water runoff. In analyzing the Hylebos Creek basin, the following four levels of storm water control were examined as basin management alternatives:

1. No Action
2. Return to 1987 Conditions
3. Stabilize Stream Channels
4. Restore to Forested Conditions

Under the No Action alternative, no capital improvement projects are proposed; only the existing level of maintenance services would continue in the basin. An annual maintenance program cost of $148,000 was estimated, based on county-wide averages. Current King County Drainage Manual standards (King County, 1990d) would determine release rates from new onsite detention facilities. This standard requires that: (1) onsite facilities be designed to produce post-development peak release rates no greater than the 2- and 10-year return rates for a 24-hour duration storm, based on the SCS Curve Number method; and (2) that pond volumes include a 30 percent factor of safety.

The second strategy would restore flow peaks to the 1987 conditions which were used as a baseline for HSPF model calibration. Since 1987, many land use changes have occurred in the basin due to continuing development, and the basin now experiences flows exceeding 1987 levels. This strategy requires four new regional detention ponds, enhanced detention volume at an existing regional facility, and current levels of maintenance service. As with the No Action alternative, the Drainage Manual Standard would apply to new development. The anticipated benefits of this strategy are the control of flood damage to residences and the partial reduction of flows. Loss of habitat diversity, channel and bank erosion, and sedimentation would continue to occur if this alternative were implemented. Intrinsic values of the stream system beyond that of surface water conveyance would be lost.

Stabilizing stream channels to limit erosion and minimize the loss of woody debris requires that flows be reduced below 1987 levels. In addition to the benefits achieved by the second strategy, this alternative would reduce the rate of erosion and limit sedimentation problems. Habitat improvement projects would help restore diversity as the system readjusts to stable flows.

Used to size regional detention facilities, a Stream Stability Standard would require post-development 2- and 10-year return period flows to meet forested 10- and 100-year flows, and a post-development 100-year flow to match a logarithmically extrapolated value (King County, 1990e). A Stream Protection Standard would apply to onsite detention facilities. This standard requires that post-development 2-year flows be released at 70% of the pre-development 2-year rate, which in turn requires approximately one and one-half times the storage required by the current Design Manual standard. Larger stream buffer widths would be instituted to preserve stream corridors and undisturbed overbank areas. Clearing limitations would preserve forest cover to limit future flow increases.

Under the last alternative, all flows from regional and onsite detention would be limited to the Stream Protection Standard. Capital improvements would include high-flow bypass pipelines to prevent storm flows from entering the stream system. Although not modeled, downzoning of all uncommitted land to rural densities and retrofitting of existing onsite detention to maximum volumes would likely be required to achieve a forested flow condition. In-stream habitat restoration projects could be completed without danger of the continuously increasing flows that result when stormwater is not controlled.

Potential projects included in any of the four alternatives were screened for engineering practicality (Is the solution technically possible?), effectiveness (Have similar projects effectively achieved flow control goals?), and institutional feasibility (Are there intractable property owners or interjurisdictional policy problems?). After this feasibility screening, each flow reduction solution was tested with the HSPF model. The solutions considered represent the range of engineering and land-use regulations commonly employed by local stormwater management agencies to solve surface water-related problems.

RESULTS AND DISCUSSION

The results of this study, which considers only Public Sector costs, are summarized in Table 1. The No Action Alternative has no capital improvement cost, although annual maintenance costs can be expected to increase as the effects of urbanization continue to degrade the stream system. Capital improvement costs for flow control and channel stabilization more than doubled between Alternatives 3 and 4, although a corresponding gain in benefits to the system would not occur. In contrast, only a relatively small increase in cost above Alternative 2 is required to implement a stream stability strategy. The Design Manual onsite detention standard effectively reduced peak flows for frequent events, whereas the regional detention facilities reduce flow rates for all events. This implies more effective flow control under Alternative 3.

Table 1
COST COMPARISON OF ALTERNATIVE BASIN SOLUTIONS

	TOTAL CAPITAL ALTERNATIVE	ONSITE DETENTION PROJECT COSTS	ADDITIONAL LAND USE STANDARD REGULATIONS
1. No Action	None	Drainage Manual	None
2. Return to 1987 Conditions	$4,270,000	Drainage Manual	None
3. Stabilize Stream Channels	$4,980,000	Stream Protection	Larger buffers Clearing limits
4. Restore Streams to Forested Conditions	$11,900,000	Forested	Larger buffers Clearing limits Downzones

Costs for constructing the necessary capital projects to restore forested flow conditions to the stream system are estimated to exceed $1,000 per acre for the entire basin under Alternative 4. Costs would greatly increase if the physical habitat and water quality were completely restored to original forested conditions. The practical political difficulties of large scale downzoning may make Alternative 4 difficult to implement. In summary, reducing flows to allow stream channels to stabilize, appears to be the most beneficial basin management strategy.

Implementation of such a strategy demands effectively identifying, ranking, and solving surface water problems using a systemwide analysis. A systemwide perspective is necessary to avoid creating additional problems, and to insure that an integrated set of solutions is chosen to appropriately match the problems in the system. A systems approach to surface water management also facilitates setting realistic goals and provides a framework for evaluating those goals in a rational and coherent fashion.

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PERFORMANCE OF DETECTION PONDS DESIGNED ACCORDING TO CURRENT STANDARDS

Bruce L. Barker[1], Ralph D. Nelson[2], and Mark S. Wigmosta[1]

INTRODUCTION

Onsite detention has been widely adopted as a means to control the increased rate of runoff from urbanized areas. When an area is developed, a detention pond or vault is constructed to reduce the increased flows with urbanization. Past detention standards and design methods have not been adequate to mitigate these increased flows in King County. The sediment and pollutants associated with higher flows are ultimately deposited in estuaries of Puget Sound. Thus, the proper functioning of detention ponds in urban areas is critical to the protection of stream systems and water quality in Puget Sound.

Recent field data and new computer modeling suggest that the existing methods of detention pond design are not adequate for the hydrologic conditions found in the Puget Sound area. Peak flow releases from detention ponds designed under current standards were found to increase substantially over undeveloped conditions. This indicates that mitigation for development has not been adequate to date, and furthermore, that the detention volume to fully mitigate peak flows is actually much greater than the current methods estimate.

DETENTION STANDARDS AND METHODS IN KING COUNTY

Rational Methods

In King County, the detention of storm water runoff was first mandated by the Storm Drainage Control Manual (King County, 1979). The requirements in this manual focused on flood control. Ponds were typically designed such that post-developed 10-year flows were reduced to pre-developed 10-year flow levels (10-year standard). The method recommended for design was the Yrjanainer and Warren (Y&W) method with peak runoff rates based on the rational method. In 1985, an amendment was made requiring multiple orifices, with the intent to control a greater range of flows.

In 1987, King County conducted a field survey of the streams in urbanizing areas and found substantial damage in urban areas with onsite detention

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ponds designed according to 1979 standards (King County, 1987). The cause of the damage was three-fold. First, drainage facilities were not being maintained properly; second, inspection during construction was inadequate; and third, the methods of design did not adequately protect the stream systems from erosion.

While many of these facilities were not functioning properly because of poor design and maintenance, the ponds having better design and maintenance also failed to protect the stream system from flooding and, most notably, erosion.

Single Event Methods

Recently, more stringent detention standards have been adopted in an attempt to prevent further degradation of streams. The King County Surface Water Design Manual (King County, 1989) requires that post-developed 2- and 10-year flows be reduced to pre-developed 2- and 10-year levels respectively, with the resulting pond volume increased by a 30% factor of safety (1.3[2- 10 year] standard). The inclusion of more frequent events (2- year) in addition to the 10-year events was intended to reduce the amount of erosion by the more frequent storms. The approved design methodology is the single event hydrograph approach. The manual recommends the use of the Santa Barbara Urban Hydrograph (SBUH) method (Stubchaer, 1975), which incorporates much of the Soil Conservation Service (SCS, 1972) approach.

Other standards required by King County have sought to address, for example, the increased flow volume in addition to the peak flow. A standard recommended by the Bear Creek Basin Plan (King County, 1990) recommends that 2-, 10-, and 100-year flows be reduced to pre-developed 1/2 of 2-, 2-, and 10-year flows respectively (the "stream protection standard").

USE OF A CONTINUOUS SIMULATION MODEL TO QUANTIFY POND PERFORMANCE

The performance of detention ponds designed to existing standards was tested using the Hydrological Simulation Program-Fortran (HSPF) (U.S. EPA, 1984). This model uses mathematical relationships to describe the physical processes controlling the hydrology of the watershed. Using inputs of precipitation and evaporation, HSPF computes the amount of discharge to the creek continuously through time from surface, shallow sub-surface, and groundwater flow.

The HSPF model was calibrated to stream systems in urbanizing King and Snohomish Counties by the USGS (USGS, 1990). Using the calibrated model, a 39-year continuous record of rainfall collected at the Seattle-Tacoma Airport

station was used to create a 39-year series of flows from hypothetical but typical site developments. The flows computed by HSPF were then routed through the detention ponds designed according to current methods and the resulting performance assessed. Return periods for the discharge from each pond tested were computed using a Log-Pearson analysis (U.S. Water Resources Council, 1977).

A total of 12 different detention ponds representing six different methods and standards, and two different land uses were evaluated in the tests. The design methods included the Y&W and SBUH methods. Pond release standards and design methods are summarized in Table 1.

Table 1
DETENTION POND DESIGNS TESTED.

Detention Pond	Design Method	Release Standard
1979 Design Manual	Y&W	10-year Single Orifice
1979 Design Manual	Y&W	10-year Multiple Orifice
1989 Design Manual	SBUH	24-hr event 1.3(2-10 year)
1990 Bear Creek Std	SBUH	24-hr event Stream Protection

The ponds were sized for 25- and 50-acre site conversions of forest to commercial and resi-dential land uses on till soils. The commercial site is assumed to be 100% impervious and the residential site is assumed to be 23% impervious with the remaining area covered by grass.

SIMULATED POND PERFORMANCE

Existing Methods and Standards

The different methods and standards evaluated for the tests produced a wide range of pond volumes (Table 2). It is clear that the 1989 Design Manual Standard provides substantially more detention volume than past standards. This increased volume is reflected in the performance of each detention pond.

Table 2
DETENTION VOLUMES FROM CURRENT DESIGN METHODS.

	Volume (inches)	
Detention Pond	Commercial	Residential
1979 Design Manual	0.51	0.19
1989 Design Manual	1.99	1.19
Bear Creek Standard	3.69	2.72

Figure 1 compares the performance of the detention ponds tested for a forested site converted to commercial and residential land uses. The ponds designed according to the 1979 manual performed the worst, with 10-year flows from the commercial site pond increasing by a factor of 10 over pre-developed levels. Ponds designed according to the 1989 Design Manual performed substantially better, with 10-year flows from the commercial site increasing by a factor of 2 over pre-developed levels. Flows from the pond designed according to the Bear Creek stream protection standard, which is intended to control 10-year flows to a pre-developed 2-year flow level, also increased by 30% over pre-developed 10-year levels. Overall, ponds designed for residential development densities performed better than the commercial sites. Flows from the 1979 manual, 1989 manual, and Stream Protection ponds changed by 350%, 20%, and -10% respectively.

This generally poor performance is the result of the ponds filling and overtopping at a frequency greater than the design storm. The reason for this is the inherent assumption in any event-based design that the pond is empty when an event begins. Because pre-developed runoff rates in the Puget Sound area are low relative to post-developed rates, the ponds drain slowly and contain water for many consecutive days during the winter. Thus, when a large event occurs, the full pond volume is not available and the pond overtops. When a detention pond is full, pond inflows are not detained, and the pond outflow nearly equals the inflow, thus increasing the potential for downstream flooding and erosion.

The multiple orifice configuration tended to increase the time for the pond to drain, thus making it more susceptible to overtopping than the ponds designed with a single orifice.

Additional Volume Required to Control Peak Flows

Examination of discharge hydrographs from the ponds designed according to the SBUH method indicates that it takes from five to ten days to reach maximum discharge during a storm event. Therefore, the design storm event, or design series of events, should be of similar length.

The simulated ponds designed by the SBUH method were redesigned using a 7-day event in an effort to improve pond performance. A 7-day duration design storm based on a modified distribution developed by Schaefer (1990) was used. The performance of ponds designed with this 7-day storm are shown in Figure 2 for two design standards. The pond designed to the 2-10 standard matches the pre-developed peak flow, and the pond designed with the stream protection standard did not overtop during the simulation period. This indicates the ponds are performing as designed.

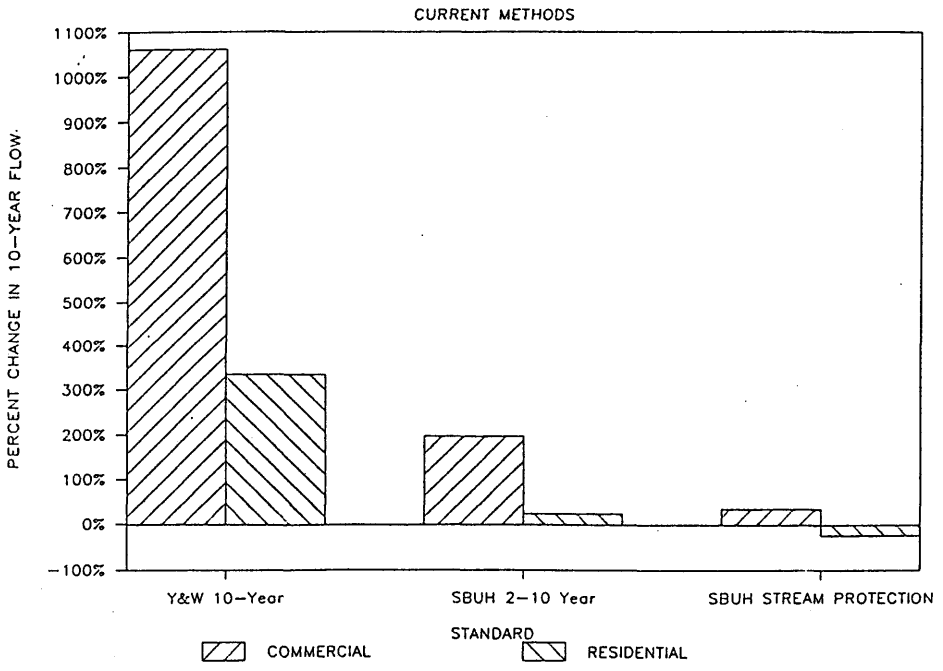

Figure 1.
PERCENT CHANGE IN PRE-DEVELOPED FLOW: CURRENT METHODS.

The ponds sized with the 7-day event produce detention ponds that are larger than volumes determined by existing standards, and so have obvious implications for development costs. For example, a commercial development pond requires 50% more detention storage with a 2-10 release standard, and 57% more storage with a stream protection release standard, over existing design methodology. The increased detention storage is considerably less with residential developments. The increase is approximately 23% with a pond release rate of 2-10, and 14% with a stream protection standard.

SUMMARY

Past onsite detention methodology has not been effective at controlling increased flows associated with urbanization. Increased flows have caused flooding and erosion damage to stream systems. These increased flows transport sediment and pollutants to Puget Sound, which is the final receiving body for streams in King County.

The performance of detention ponds designed according to various standards indicates that none of the methods or standards that have been used in King

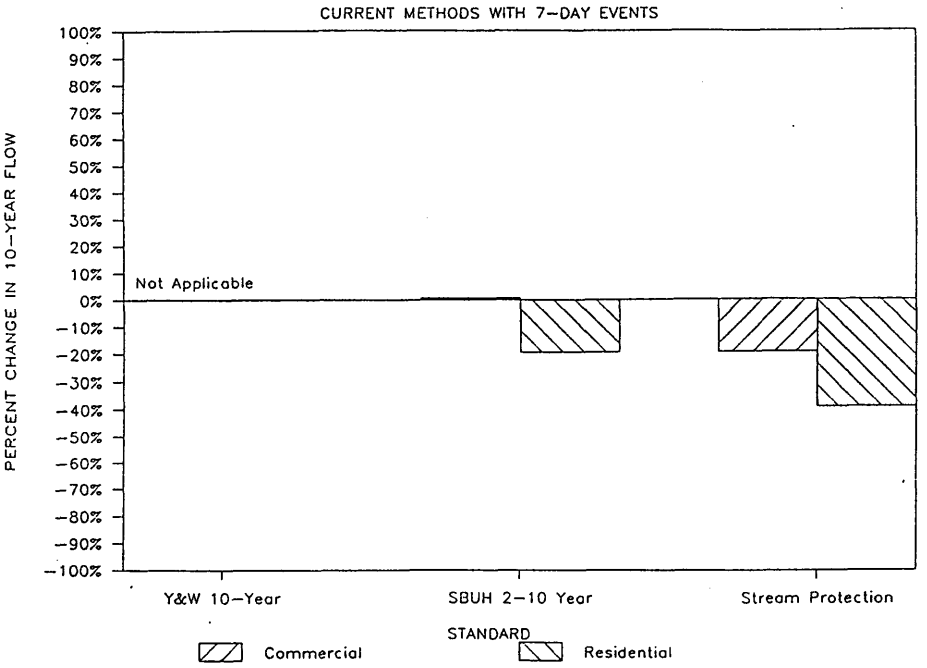

Figure 2.
PERCENT CHANGE IN PRE-DEVELOPED FLOW: CURRENT METHODS WITH 7-DAY EVENTS.

County to date reduce flows to the design level. The underlying cause of this is the assumption that the ponds are empty when the storm event begins. The continuous model shows this not to be the case, and that the ponds designed according to event methods operate partially full for periods of several consecutive days at a time throughout the winter.

The pond performance was improved by designing the ponds using a longer design storm. This storm was chosen to be 7 days to match the apparent length of time ponds drain in the winter. The ponds designed with the 7-day event matched the design goals. However, they were considerably larger than ponds designed by current standards, as much as 50% larger for commercial ponds and 20% larger for residential ponds.

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PUGET SOUND

RESEARCH '91

OCEANOGRAPHY IN PUGET SOUND

Session Chair:

Alyn C. Duxbury, University of Washington

INTRODUCTION

Alyn C. Duxbury[1]

In the field of oceanography there are those who are interested in the mechanics of estuaries, how their waters circulate, what drives the circulation, and how and why patterns of circulation and water properties change in both time and space. These oceanographers use a variety of data resources, often historical, to determine what is happening at large in a complex system. Detailed studies are then conducted to determine specific information that is necessary to explain the importance of discrete processes that combine to create the larger picture. We look at the forest first to gain a general quantitative appreciation of its appearance. Then we look at the trees to understand how the forest functions and maintains its structure.

This morning we have seven presentations that speak to the properties of the greater Puget Sound region. The first two presentations look at surface circulation in the Strait of Juan de Fuca as defined by the paths of drifting objects. They show that during storm events surface water can move eastward in the Strait and that permanent eddies are present that cause the accumulation of drifting material to be enhanced in specific shore areas. These studies are followed by a detailed look at how the net circulation of the Sound proceeds, the role that mixing zones play in creating recycling of water, and the effect circulation has on controlling the residence time of water and concentrations of materials in true solution or suspension in the water.

The next two papers are studies of a sub-area of the Sound, Hood Canal. Here the behavior of dissolved materials in response to both biological and chemical processes is discussed for a region that has reduced water circulation and that is altered significantly over the annual cycle by localized biological activity which changes the chemical properties of the water.

In Puget Sound the flow and water characteristics are nonhomogeneous. When a flow of waste material is added to the Sound, it is very difficult to monitor the position and changing properties of the waste plume in time and space. Yet this is necessary to understand the impacts of a waste stream on the ambient water. New tools are coming into use than can acoustically differentiate between the waste stream and the surrounding water. The application of Acoustic Doppler Current Profiler systems to this task is presented in the sixth paper.

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Last but not least, we all are interested in the ongoing effort to determine the earth's response to global warming. Temperature measurements have so much variability place to place and over time-scales of days, weeks, months, and years, that clear trends are not necessarily evident. In the last paper we will learn that if long-term temperature measurements are divided up into clear days *versus* cloudy days, then significant temperature trends can be shown to exist in the Puget Sound region.

I am pleased to present these speakers to you this morning.

1875 FLOATABLE WRECKAGE DRIVEN INLAND THROUGH THE STRAIT OF JUAN DE FUCA

Curtis C. Ebbesmeyer, Jeffrey M. Cox, and Brian L. Salem [1]

INTRODUCTION

The frequency of major oil spills in the Pacific Northwest led us to investigate where oil might be transported if a spill were to occur off the coast during a reversal of the estuarine surface flow in the Strait of Juan de Fuca (hereafter Strait; Fig. 1). Despite the known environmental consequences of floating oil, few oceanographic observations have been made of surface materials transported inland from the open sea. We collected previously unanalyzed observations derived from the aftermath of the November 1875 collision of the steamship *Pacific* and clipper ship *Orpheus* (Fig. 2).

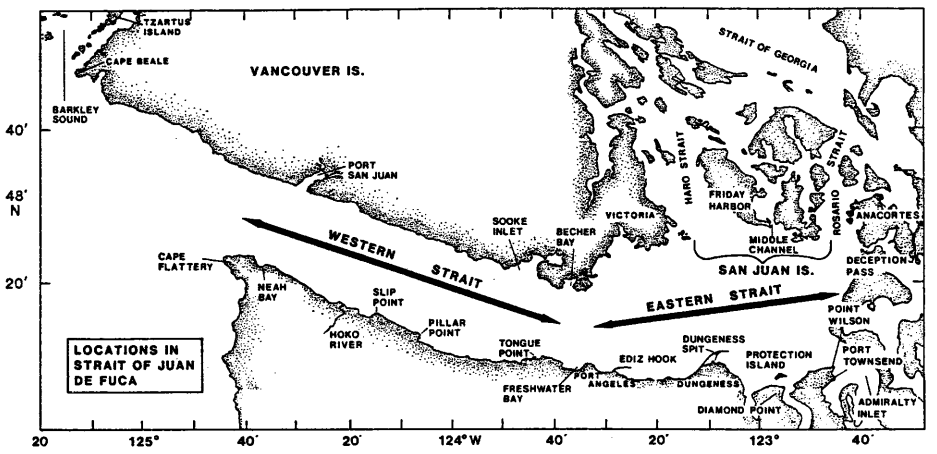

Figure 1.
LOCATIONS IN THE STRAIT OF JUAN DE FUCA.

BACKGROUND

Background information was derived from recorded oceanographic measurements, a model, and the Nestucca oil spill. Normally, the hydraulic head is greater in the eastern Strait; surface water flows seaward to the west. However, during winter storms, southerly winds along the coast elevate the surface water via Ekman transport, effectively reversing the surface pressure gradient along the Strait. As a consequence, fresher water at the western end flows eastward, thereby reversing the normal seaward estuarine flow. This

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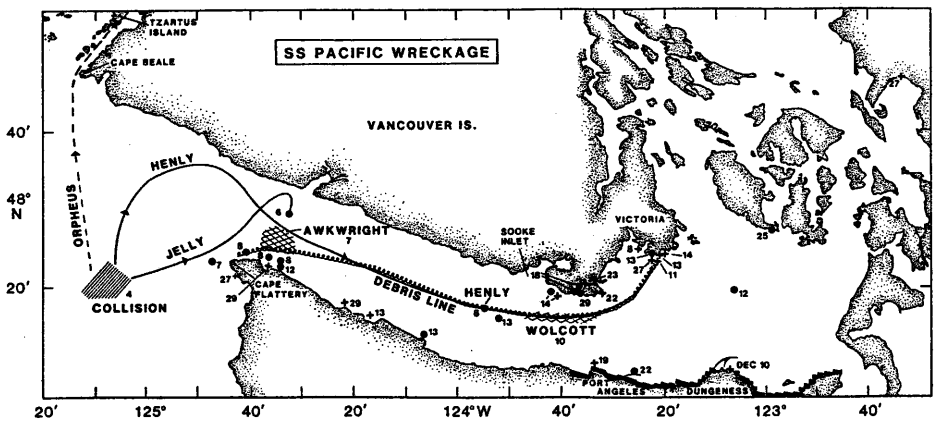

Figure 2.
LOCATION AND DATE OF RECOVERY OR SIGHTING OF THE SS PACIFIC WRECKAGE. *Notation: hatching, offshore distance at time of collision between the* SS Pacific *and the clipper ship Orpheus (the north-south position of the wreck is considered to be speculative); dashed line, approximate track of the clipper ship* Orpheus *from the site of the collision to her grounding near Tzartus Island in Barkley Sound; solid lines, approximate trajectories for the two survivors (Jelly & Henly); crosshatch, sightings of the main mass of wreckage by the vessels Awkwright and Wolcott; corkscrew, line of debris between Cape Flattery and Victoria; staircase pattern eastward from Port Angeles, scattered light wreckage; dot, recovery of survivors or bodies; +, location of prominent debris; number with dot or +, date sighted or recovered in November 1875 (one sighting, 10 December).*

lighter water tends to flow inland along the Strait's southern shore under the influence of Coriolis acceleration.

Recorded Measurements and Model

Hydrographic and current meter measurements in the Strait during 1977-1981 showed that, near the surface, reversed estuarine currents can interrupt the circulation in any month (Holbrook et al., 1983). Reversals frequently occur when a low pressure center off Washington generates southerly winds along the coast (Holbrook et al., 1980, 1983). Although most frequent during winter, this situation can occur in summer; movements of surface drifters were observed when a low pressure cell lay off the Washington coast during 23-25 August 1978 (Cox et al., 1978; Holbrook et al., 1980; Frisch et al., 1981). In the western Strait, trajectories of several drifters abruptly reversed (Cox et al., 1978; Ebbesmeyer et al., 1979).

Numerical simulations also showed that intrusions could penetrate inland, but not as far as suggested by current meter observations (Niebauer, 1980; Klinck et al., 1981; Holbrook et al., 1983). Correlations with Strait currents

revealed that coastal winds were of prime importance, with local winds having small effect on the reversals (Holbrook et al., 1980). The rate of intrusion (eastward surface current speed) was computed from Benjamin's (1968) equation for the hydraulic flow of a lens of lighter water traveling over denser water under the influence of gravity (Holbrook and Halpern, 1982; Holbrook et al., 1983). Subtracting an assumed mean westward estuarine current of 15-20 cm/s from the theoretical intrusion speed yielded an eastward speed of 25-30 cm/s (12-14 nm/day).

Nestucca Oil Spill

At about 2300 on 22 December 1988, the barge *Nestucca* and its tug *Ocean Service* collided off Grays Harbor on the Washington coast while a snapped tow line was being replaced (Gregoire and Kittle, 1989). Shortly afterward, 231,000 gallons of number 6 fuel oil (a heavy bunker C oil) escaped through a 7-foot gash in the *Nestucca* hull (Canadian Coast Guard, 1989; Kennedy, 1989). By 31 December some floatable oil had been conveyed across the Strait's entrance, and by 15 January 1989 oil had reached Cape Scott at the northern end of Vancouver Island (Fig. 3). Oil along the eastward route through the Strait was observed first on 4 January, and samples were collected between 4-15 January. Based on these observations, the oil's northward speed along the Washington coast between the spill and Cape Flattery was 18 nm/day and along Vancouver Island was 12 nm/day, while the eastward speed through the western Strait was 9 nm/day. Chemical analyses of oil samples from several locations in the Strait were compared with analyses of other types of bunker C oil stored in the eastern Strait, and the results indicated that the samples were from the *Nestucca* (U.S. Coast Guard, 1989).

From the time of the spill to the first observation of floatable oil in the eastern Strait (4 January), winds along the coast (measured at Destruction Island) were predominately from the south, a wind direction conducive to reversals in the Strait. Considering that typically in winter 2-3 surface current reversals, each lasting 2-7 days, occur each month (Holbrook et al., 1983), a number of intrusions probably developed during the weeks after the *Nestucca* spill.

RESULTS

Shipwreck Data

Editions of nine Pacific Northwest newspapers (mostly between 6 November and 10 December 1875) were examined at the University of Washington. Reports of debris, unquestionably from the *Pacific*, were arranged in chronological order. Also included were weather conditions, circumstances surrounding the collision and debris recoveries, and commentaries of the two survivors. Figure 2 describes confirmed, prominent debris found on given dates.

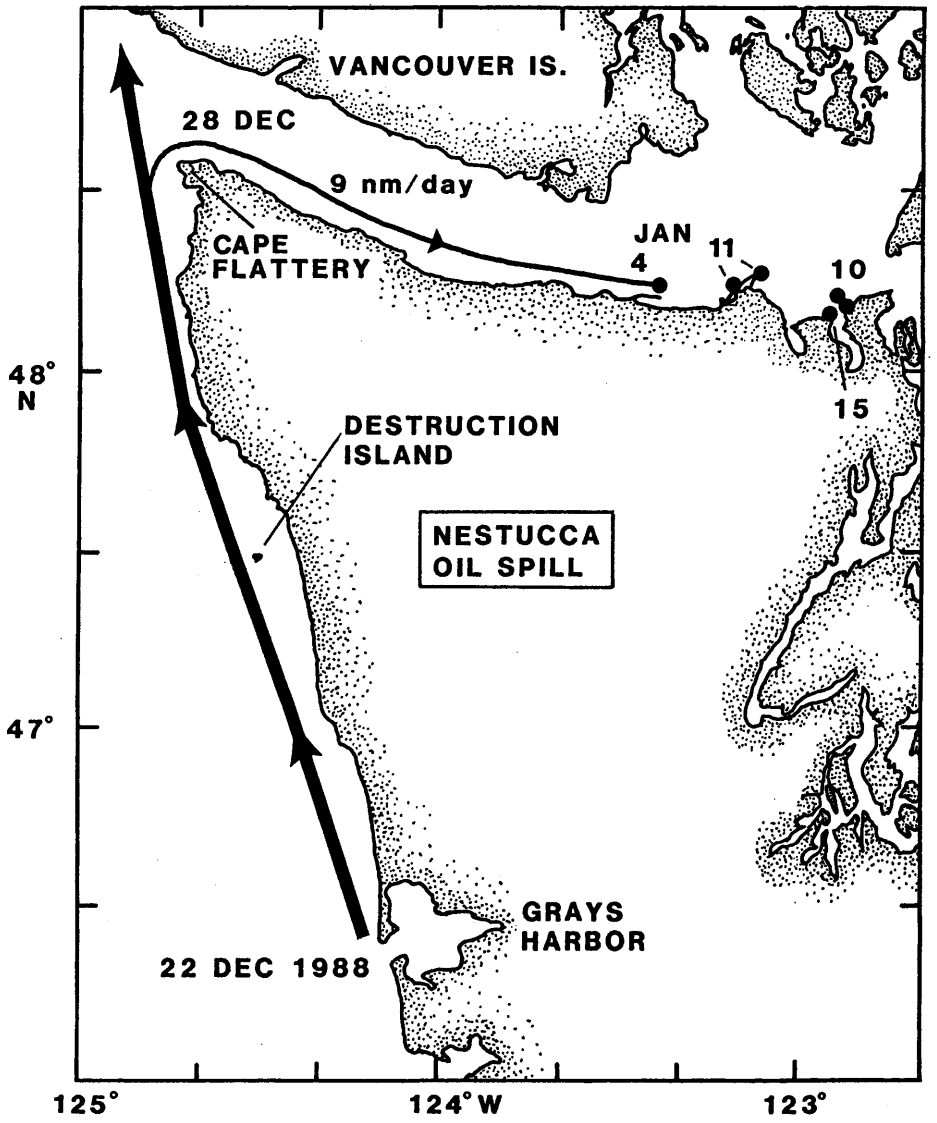

Figure 3.
DRIFT OF OIL FROM THE* NESTUCCA *SPILL ON 22 DECEMBER 1988; *dots in the eastern Strait of Juan de Fuca, chemically analyzed oil samples; line, inferred trajectory with line weight proportionate to amount of oil; numbers next to dots, January date in 1989 when oil samples were obtained.*

Collision of *Pacific* and *Orpheus*

On 4 November 1875 at the beginning of a storm, the *SS Pacific*, southbound from Victoria with 250-300 passengers, rounded Cape Flattery, collided with the northbound clipper ship *Orpheus*, and sank. The *Orpheus* was damaged only slightly. Time of the collision was ascertained from testimony of Captain Sawyer of the *Orpheus* as shortly after 2130, and testimony of the two *Pacific* survivors (Jelly and Henly), confirmed by watches on two bodies, suggests that the *Pacific* sank over a period of about an hour. As the *Pacific* was sinking, Captain Jefferson D. Howell estimated the ship was 15 to 20 miles from shore (according to Henly). Latitude of the collision is speculative because velocities of the coastal currents could not be determined at the time in question.

Shortly after the collision, the *Pacific's* boilers may have exploded, as inferred from the condition of a body (passenger Hellmuth), and from the considerable wreckage of rooms within the *Pacific's* interior, including timbers from state-rooms #30 and #41 (numbers on timbers), molding, and a ceiling beam on which passenger Moody had written a farewell. In addition, substantial parts of the *Pacific*, including the pilot house, rudder, and possibly the boilers, became detached.

Weather Reports

According to newspapers and the diary of James G. Swan (a local federal agent; Swan, 1875), a series of storms occurred during November (5, 9, 14-16, 21, 28), and apparently the first three were involved with transporting most of the *Pacific* debris into the Strait. Low barometric pressure readings at Portland, Oregon, confirmed the storms on 6, 13-17, and 29 November to 3 December 1875, but not those on 9 and 21 November (data from U.S. Signal Office, 1875). Presumably some of the storms were localized in the vicinity of Cape Flattery.

The following chronology was ascertained from observers in the vicinity of Cape Flattery: during the day of the 4th, the weather was moderate; by evening, as the *Pacific* rounded Cape Flattery, there was a strong headwind and heavy swell; and by midnight the wind was blowing hard from the southeast with a 'very bad' sea. Thus the collision occurred at the beginning of the first storm.

Debris Sightings

The quantity and variety of wreckage was extensive. According to carpenters who refurbished the *Pacific* in 1875, she had substantial dry rot and was structurally weak at the time of the collision. Wooden wreckage fell apart upon recovery and fresh wood bolted to dry-rotted wood also was evident. An explosion, mentioned earlier, coupled with dry-rotted wood may explain the extensive debris.

Newspapers indicated that shores were thoroughly searched. Scant debris was reported outside the Strait, whereas extensive amounts were found inside. Despite diligent searches only 6% of the approximately 250-300 passengers were recovered. The bodies found were reasonably well preserved and most had life preservers attached when found; thus, it appears likely that the bodies had been floating for most of the time between the collision and recovery.

Transport of Debris

Commentaries by the two *Pacific* survivors, regarding land they passed as they clung to wreckage, suggested some general aspects of the surface currents. Jelly drifted close to Cape Flattery, then within a mile of Vancouver Island, and shortly thereafter was rescued off Port San Juan. Henly drifted within sight of the revolving light at the Cape Beale lighthouse, then close to Vancouver Island, and was rescued between Pillar Point and Sooke Inlet (Lockley, 1926). These observations suggest two trajectories, the one for Jelly indicating direct intrusion into the Strait and that for Henly, a brief northward movement followed by a long drift inland (Fig. 2).

Information reported in newspapers was sufficient to estimate the speed at which wreckage was transported from 20 miles west of Cape Flattery to 80 miles inland at Victoria. Effects of wind on the wreckage were omitted because wind observations in the Strait were not available, and also because windage on the wreckage could not be ascertained. Over an 11-day period the largest mass of wreckage was reported at three places (Fig. 2): (1) off Neah Bay during the afternoon of 7 November (vessel *Awkwright*); (2) north of Port Angeles in the afternoon of 10 November (vessel *Wolcott*); and (3) in the vicinity of Victoria during 11-14 November (many recoveries). These data, in addition to those of the collision itself and the rescue of the two survivors, were entered on a graph of distance versus time; a linear regression was computed using the center of each observation (Fig. 4). This yielded a regression slope equivalent to speed that explained approximately 92% of the variance (19 cm/s; 9 nm/day). The regression speed probably represents an average; it was evident that some wreckage traveled more quickly. On 8 November, debris began to appear at Victoria, equivalent to a speed of approximately 20 miles per day, a value taken herein as the fastest inland speed.

Debris Concentration

Commentaries of observers aboard the search vessels showed that *Pacific* debris became concentrated in well-defined lines and patches in open water and at specific locations along the shore. An approximately 60-mile-long line of debris formed after the first storm, as noted in a letter to Professor George Davidson (Fox, 1910). The debris line, directed to the southern end of Vancouver Island, coincides with the many recoveries of bodies and wreckage

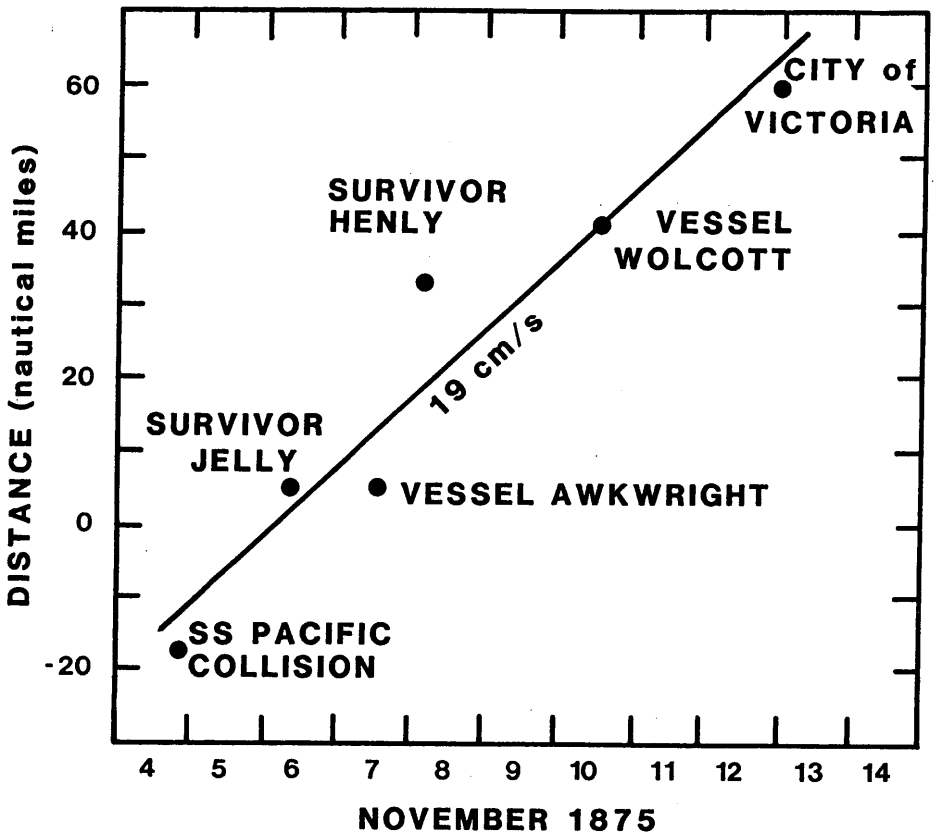

Figure 4.
DISTANCE VERSUS TIME FOR SELECTED WRECKAGE FROM THE SS PACIFIC. *The straight line represents a linear regression fit to the observations, where r equals the regression coefficient and speed (19 cm/s) corresponds to the slope of the regression. Notation: SS PACIFIC COLLISION, collision of vessels Orpheus and Pacific; JELLY & HENLY, the two survivors; AWKWRIGHT & WOLCOTT, sighting of the main mass of wreckage by the vessels Awkwright and Wolcott; and VICTORIA, frequent reports in the vicinity of Victoria.*

made there. A large patch was noticed by survivor Henly as he drifted inland on some wreckage; the next day a vessel approaching to rescue Henly gave another perspective on the debris's extent.

The pattern of floating materials arriving at the shore in the eastern Strait was inspected by superposing the 1875 *Pacific* wreckage positions on the 1978 drifter recoveries (Fig. 5). Summing these percentages, 76% of the recoveries were on northern shores and 24% along the southern shores of the eastern Strait. In contrast, in the western Strait none of the *Pacific* debris was found

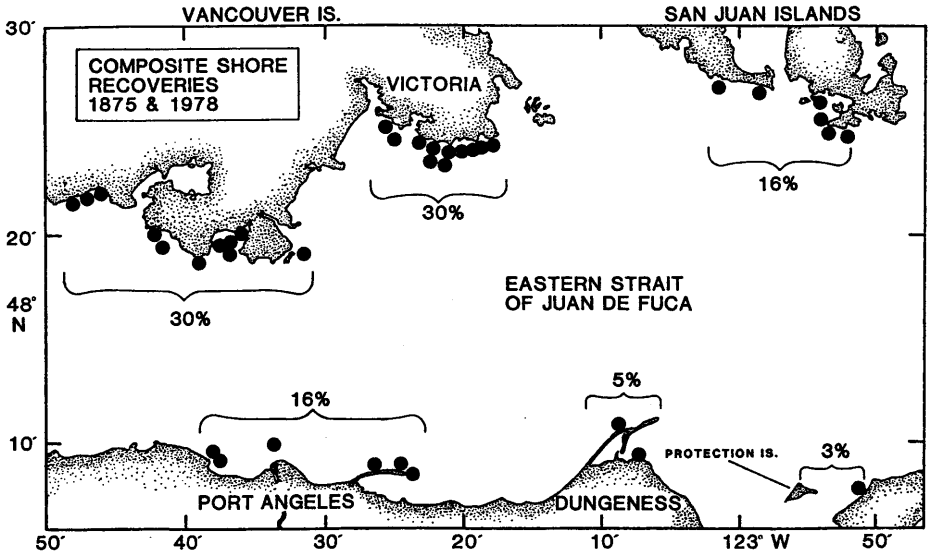

Figure 5.
COMPOSITE SHORE REPORTS OF SS PACIFIC WRECKAGE (1875) AND DRIFTERS (1978) IN THE EASTERN STRAIT OF JUAN DE FUCA.

west of Sooke Inlet along the northern shores (Fig. 2). Using the same technique on other background information indicates that Nestucca oil (Fig. 3) was found near the same locations as *Pacific* debris and oceanographic drifters. The correlation between shore reports from all data sources suggests that floating materials tend to beach at specific locations in the eastern Strait.

DISCUSSION

Observations by pioneers and oceanographers have been compiled herein regarding floatables driven inland through the Strait of Juan de Fuca. As information has accumulated, repeating patterns have emerged which will further the understanding of oil spills. During our research, we noticed that significant new information should have been gained from the distribution of oil transported by coastal and estuarine currents. However, the combination of numerous spills and limited manpower has delayed the interpretation of much of the data amassed by state and federal agencies. During the relatively short interval between the recent oil spill in 1988 and the writing of this paper, information concerning the spill already has become scattered. Comprehensive reports prepared concerning oceanographic measurements made in relation to major spills will add significantly to the base of information now available.

A comparison of inland intrusions with coastal currents is enlightening. Floatable oil from the *Nestucca* barge was carried northward to Cape Flattery at an average speed of 15 miles per day, and then a small amount was transported inland at 9 miles per day. Wreckage from the Pacific moved inland at 9 to 20 miles per day and surface drifters, during the summer intrusion of 1978, at 18 miles per day. Thus, on occasion, northward coastal and reversed estuarine current speeds are comparable. Also, significant amounts of floatable materials can move either north along the Vancouver Island coast, with a small amount heading inland, or mostly inland to the head of the Strait.

Only a small number of observations are available with which to derive the inland movement of floatable materials. Additional sources of information can augment the data base. For example, debris from several hundred vessels also wrecked in the Strait's approaches may have been transported to the eastern Strait (see Gibbs 1957, 1968). Another source may be derived from redwood logs carried northward along the coast beyond the northern limit of redwood forests in southern Oregon (Davidson, 1889). Surveys of these logs along the Strait shore may reveal the locations where floatables tend to accumulate when transported inland by intrusions.

CONCLUSIONS

Conclusions from this study of the collision between the steamship *Pacific* and clipper ship *Orpheus* may be summarized as follows: (1) substantial amounts of floatable material can be transported from oceanic regimes through the Strait of Juan de Fuca to the entrances of Puget Sound and the Strait of Georgia (on the order of 100 miles inland); (2) the inland transport speed of the *SS Pacific* wreckage was comparable to that of surface drifters, a recent major oil spill, and a dynamic model; (3) during episodes of reversed estuarine currents, extensive lines and patches of floatable material form, with significant amounts of the material tending to beach at specific locations in the eastern Strait.

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EDDY INDUCED BEACHING OF FLOATABLE MATERIALS IN THE EASTERN STRAIT OF JUAN DE FUCA

Curtis C. Ebbesmeyer, Carol A. Coomes, Jeffrey M. Cox, and Brian L. Salem [1]

INTRODUCTION

The frequency of major oil spills in the Pacific Northwest prompted us to examine the extensive information regarding surface drifters (drift cards; drift bottles; drift sheets; shipwreck debris) and tidal currents (field observations; numerical and hydraulic models) in order to understand where spilled floating oil might be transported in the eastern Strait of Juan de Fuca (hereafter eastern Strait; Fig. 1). Drifters released in widely varying regions and recovered in the eastern Strait were compared, including releases off the Pacific Coast and in the Strait of Georgia, Admiralty Inlet, and Elliot Bay (Fig. 1). Recoveries in identical areas, regardless of release area, could then be compared with patterns of tidal currents derived from numerical and hydraulic models and field observations.

Results from two kinds of searches were compared because interpretation of drifter recoveries can be complicated by the variability of human populations; i.e., drifters might be found most frequently where beaches are routinely walked. If the drifters are found in similar locations as a result of passive and active searches, confidence increases that the recovery patterns reflect natural phenomena and not artifacts of the searches.

Data

Drifter recoveries were ascertained from seven data sets, and the number and position of prominent tidal eddies were determined from hydraulic and numerical tidal models as confirmed with field studies.

Drifters

Active searches were conducted for debris from two shipwrecks (Table 1). After a collision 20 miles west of Cape Flattery on 4 November 1875, debris unquestionably from the SS Pacific was found inland within the eastern Strait. As a result of a storm in January 1904, debris from the steamer Clallam was found at specific locations in the eastern Strait. The high death toll from the shipwrecks (Pacific, about 250; Clallam, about 55) led to intensive searching by numerous vessels. During August 1978, 91 drift sheets (measuring approximately 1x1x0.003 m), were distributed over the eastern Strait; later 19 were found beached. The drift sheets were located during numerous sorties by low-

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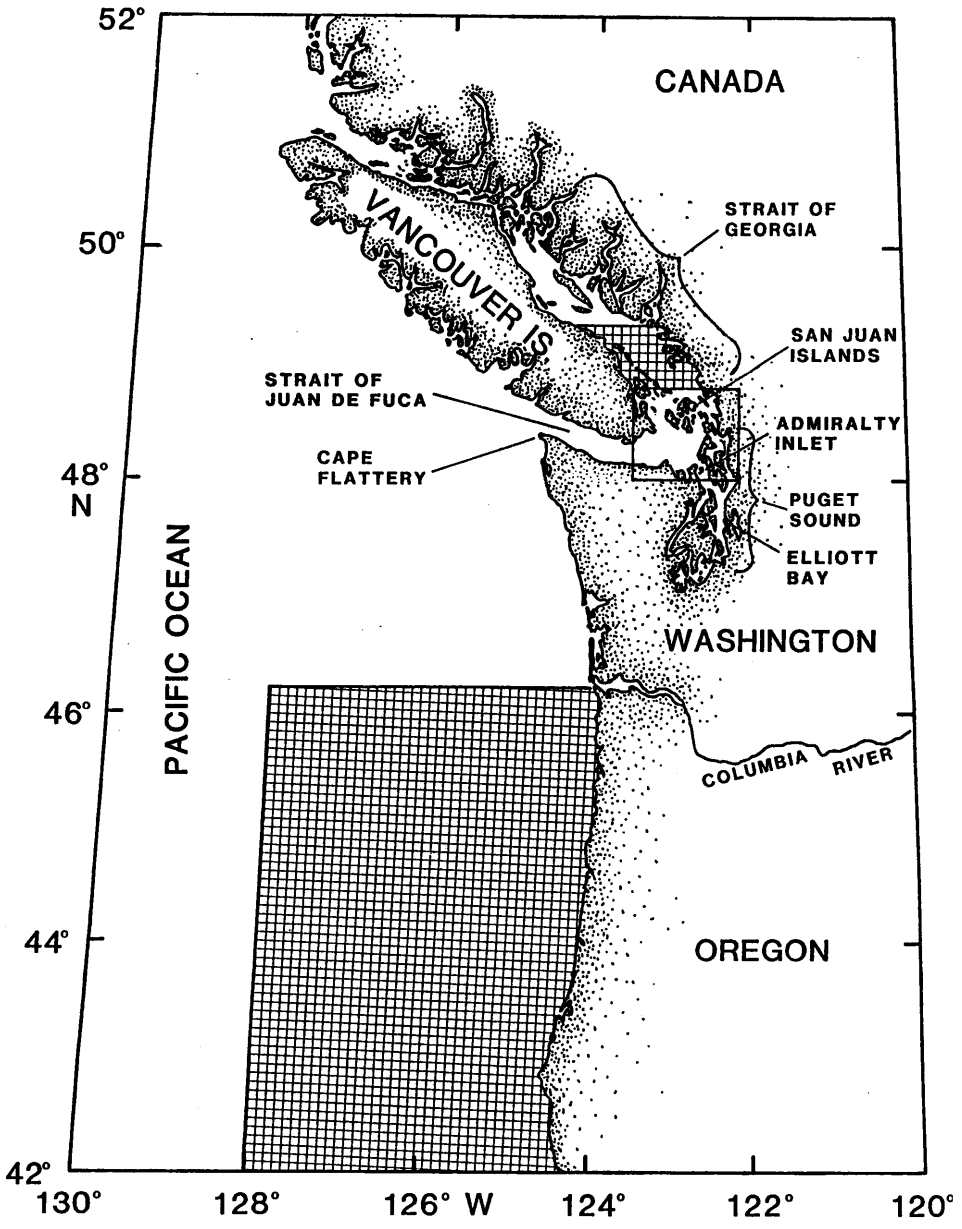

Figure 1.
GENERAL LOCATIONS WHERE DRIFT MATERIALS WERE RELEASED *(cross hatched, Admiralty Inlet, and Elliott Bay) in relation to the study area in the eastern Strait of Juan de Fuca.*

Table 1.
SEVEN DATA SETS USED IN PRESENT STUDY.

Release location	Type of drifter	Year of release	(Number of releases)	Total number of recoveries	(Number of drifters released)	Ref.
Active searches (see Fig. 4)						
Cape Flattery	Debris (Pacific)	1875	(1)	17		(a)
Eastern Strait	Debris (Clallam)	1904	(1)	24		(b)
Eastern Strait	Drift sheets	1978	(1)	19	(91)	(c)
Passive Searches (see Fig. 5)						
Oregon coast	Drift bottles	1961-1967	(44)	15	(10,525)	(d)
Georgia Strait	Drift bottles	1926-1931	(25)	64	(1,420)	(e)
Admiralty Inlet	Drift cards	1980	(9)	137	(889)	(f)
Elliott Bay	Drift cards	1983-1984	(13)	138	(3,503)	(g)
Total			(94)	414	(>16,428)	

Notes:
(a) *Ebbesmeyer et al. (1990); 17 debris objects used in study.*
(b) *Observations from regional newspapers; 24 debris objects used in study.*
(c) *Cox, et al. (1978).*
(d) *Wyatt, et al. (1971); data from charts 6101-6706.*
(e) *Waldichuk's (1958) Figs. 1-25; no releases in 1930.*
(f) *Cox et al. (1980); releases 10700-900, 11200-400, 13200-400.*
(g) *Ebbesmeyer (1985).*

flying aircraft utilizing accurate microwave ranging electronic equipment. Common to the three active searches is the fact that the releases were made either during (shipwrecks) or shortly after (drift sheets) particular storms. For this reason the drifters were probably affected by currents directed inland through the western Strait of Juan de Fuca (current reversals) as opposed to the normal seaward- or westward-flowing mean current direction (Ebbesmeyer et al., 1990). Figure 4 shows the composite recoveries from active searches.

Passive searches were conducted for drift bottles released off Oregon and in the Strait of Georgia, and for drift cards released in Puget Sound (Fig. 1). These drifters were released in batches at specific locations during months spanning a composite year. An average of 8 releases (range of 3-25), were made in each month (Table 2). The drifters were released in 18 different years (Table 1). Therefore, the composite recovery pattern described herein is conditioned by a variety of oceanographic and meteorologic conditions occurring in a substantial number of years and months. Figure 5 shows the composite recoveries for the passive searches.

Table 2.
MONTHS IN WHICH DRIFTERS WERE RELEASED *(see Table 1 for references).*

Month	Number of releases: Oregon coast	Cape Flattery[1]	Eastern Strait[2]	Georgia Strait	Elliott Bay[3]	Admiralty Inlet[3]	Total
January	5		1		1		7
February	5				1		6
March	2				1		3
April	5						5
May	1			3	1		5
June	2			1	2		5
July	6			9	1	9	25
August	2		1	12	1		16
September	3				1		4
October	4				1		5
November	4	1			2		7
December	5				1		6
Total	44	1	2	25	13	9	94

[1] Wreck of the *SS Pacific.*
[2] Wreck of the Steamer *Clallam* and drift sheets.
[3] Puget Sound.

Tidal Eddies — Tidal eddies in the eastern Strait have been documented with hydraulic and numerical models, as well as with oceanographic field observations. Locations of 14 prominent eddies, summarized in Table 3, are shown in Figure 2. Each eddy was observed in the hydraulic model, and 9 with the numerical model and field observations. Crean (pers. comm.) computed residual tidal velocity vectors averaged over a month with his GF7 numerical model utilizing 61 tidal constituents. Figure 3 shows the residual velocity direction without regard for speed.

RESULTS

General Recovery

Approximately 2% of 16,428 drifters released on 94 occasions were found on eastern Strait shores. The percentage recovery varied with distance of the releases from the eastern Strait (see Fig. 1): 0.1%, offshore Oregon (~600 km); 4%, Puget Sound (Elliott Bay; ~100 km); 5%, Strait of Georgia (~100 km); 16%, Admiralty Inlet (~30 km); and 23%, eastern Strait (0-25 km). These percentages do not total 100% because most recoveries were made near the releases and are not presented here.

Active Versus Passive Recoveries — Comparisons were made between data sets from active and passive searches (Table 4). To do this, drifters from the

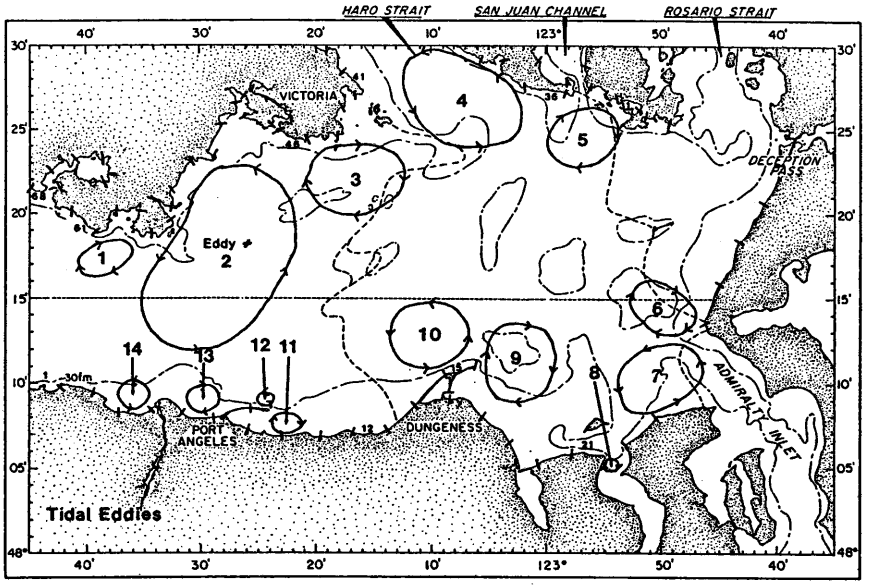

Figure 2.
LOCATIONS OF TIDAL EDDIES (1-14; TABLE 3). *Ticks divide the shore into segments 1-68.*

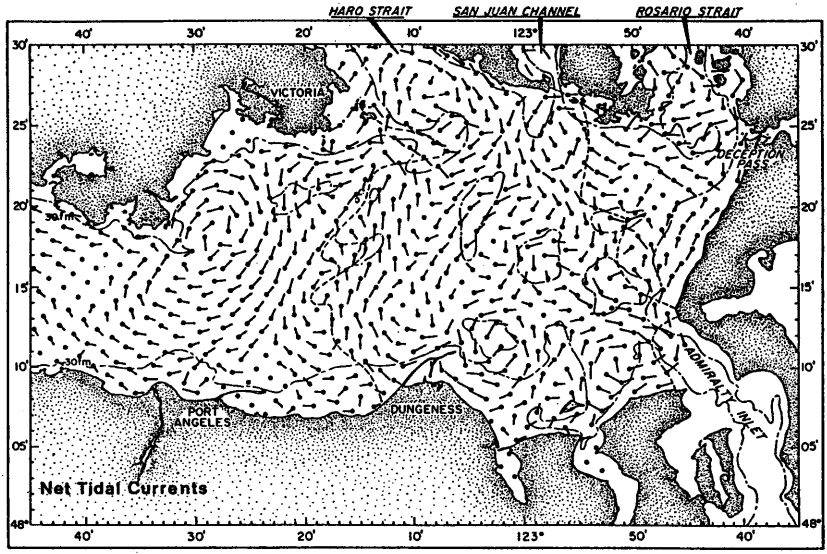

Figure 3.
DIRECTION OF NET CURRENTS COMPUTED OVER A 30-DAY INTERVAL USING CREAN'S (1983) GF7 NUMERICAL MODEL. *Dots indicate location of the computation, and sticks point in the current direction without regard for speed.*

Table 3.
FOURTEEN TIDAL EDDIES IN THE EASTERN STRAIT OF JUAN DE FUCA, *referencing observations confirming their existence in models and in the field.*

Eddy No.	General location (see Figs. 2,3)	Formed on tidal phase	Model confirmation[1]	Field confirmation
1.	Becher Bay	Ebb	Hyd.	
2.	Race Rocks	Flood	Hyd., Num.	Crean (1983)
3.	Victoria	Ebb	Hyd., Num.	Crean (1983)
4.	San Juan Is.	Ebb	Hyd., Num.	Crean (1983)
5.	Lopez Is.	Ebb	Hyd., Num.	
6.	Partridge Pt.	Ebb	Hyd., Num.	
7.	Pt. Wilson	Ebb	Hyd., Num.	Davidson (1889)
8.	Diamond Pt.	Flood	Hyd.	Ebbesmeyer (1988)
9.	Dungeness Spit	Flood	Hyd., Num.	Frisch et al. (1981)
10.	Dungeness Spit	Ebb	Hyd., Num.	Ebbesmeyer et al. 1979)
11.	Ediz Hook	Flood	Hyd.	Ebbesmeyer et al. 1979)
12.	Ediz Hook	Ebb	Hyd.	Ebbesmeyer et al. 1979)
13.	Elwah R. Delta	Flood	Hyd.	
14.	Elwah R. Delta	Ebb	Hyd.	

Note:
[1] Hyd. – *Hydraulic model of Ebbesmeyer et al. (1979).*
Num. – *Numerical model of Crean (1983).*

seven data sets were tabulated within five areas of the eastern Strait (Figs. 4, 5): northern shores, southern shores, vicinity of Victoria, vicinity of San Juan Channel, and Dungeness Spit. After each data set was tabulated, the percentage of total recoveries in a given data set was calculated. These percentages were then averaged by area for the active and passive searches. The following averages were obtained for the active (passive) searches: northern shores, 76% (70%); southern shores, 24% (30%); and total of Victoria, San Juan Channel and Dungeness Spit, 62% (66%). The similarity of these percentages, considering also that they lie within 1-2 standard errors of one another, suggests that comparable results were obtained from active and passive searches.

Combined Data Sets—The percentage of recoveries computed separately for the seven data sets were averaged to yield a composite picture (Table 4). Further computations showed that the standard errors equaled 3-11% of the mean values computed for the north shore, south shore, and three subregions. This result suggests that the recoveries are insensitive to release location and type of drifter.

Two Asymmetries — Two asymmetries were apparent in the recovery patterns. First, 73% of the recoveries were made on the northern shores, versus 27% on the southern shores. Since these mean percentages differ by 15 standard errors, there is confidence that the recoveries along the northern

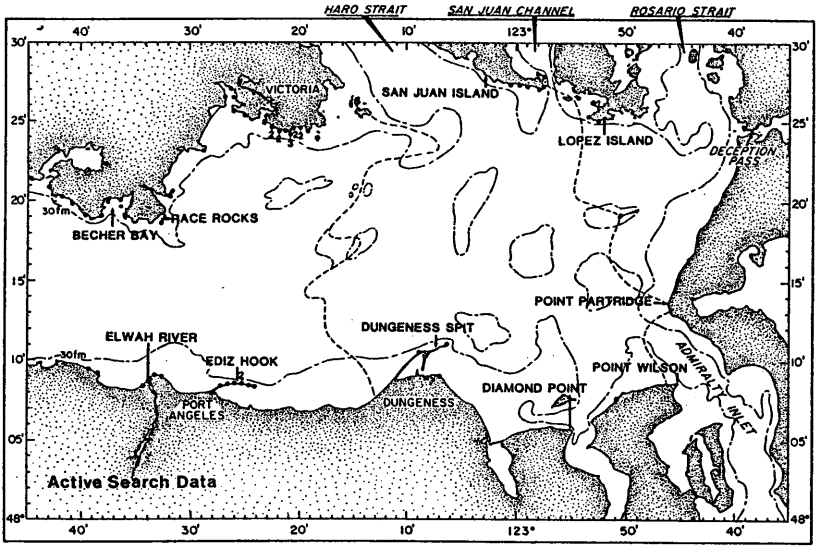

Figure 4.
COMPOSITE RECOVERIES FROM THREE ACTIVE SEARCHES (TABLE 1). *Dots indicate individual recoveries, and numbers multiple recoveries.*

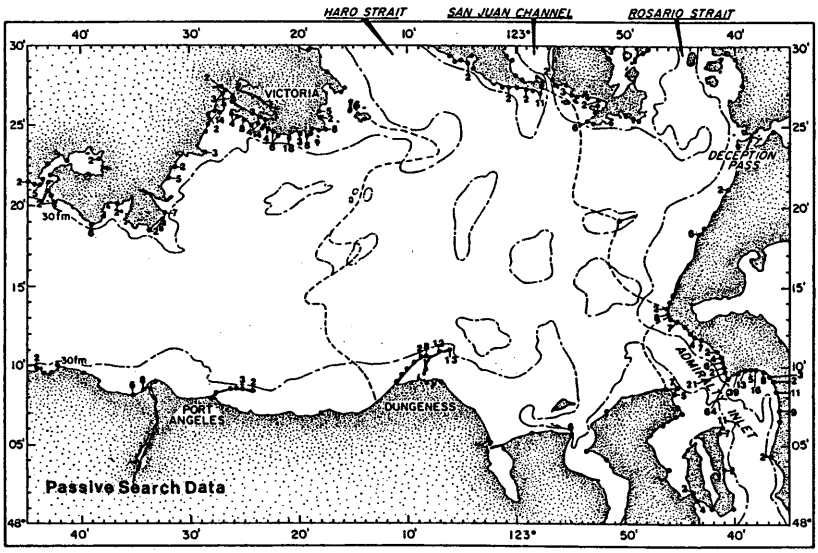

Figure 5.
COMPOSITE RECOVERIES FROM FOUR PASSIVE SEARCHES (TABLE 1). *Dots indicate individual recoveries, and numbers multiple recoveries.*

shores substantially outnumber those along the southern shores. Within these general areas, comparison of active and passive searches showed that the drifter recoveries were localized to specific areas.

To describe the specific areas, the drifters were tabulated within 68 segments measuring 4.07 kilometers (Fig. 2). Calculated for each segment was the number of drifters recovered as a result of active and passive searches, as well as the total number of recoveries. These numbers were then divided by the total sample to obtain recovery frequencies for each segment (Fig. 6). The frequencies were ranked from highest to lowest, and then the cumulative frequency was calculated, starting with the highest frequency and proceeding to the smallest frequency (Fig. 7). The cumulative frequency of recovery yielded the following description of the localized asymmetry: most drifter recoveries were concentrated such that 50% were found on only 12% of the shore, and most of the shore received few drifters, such that along 50% of the shore 0% (active) to 10% (passive) of the drifters were found.

Recoveries In Relation To Tides — Explanations for the observed asymmetries in drifter recovery were found by comparing the frequencies in the segments with positions of the tidal eddies (Figs. 2, 3). The highest frequency occurred in segment #46 located in the net onshore flow between eddies #2 and #3 in the vicinity of Victoria. The second highest frequency occurred along the outer half of Dungeness Spit in segment #15 in the vicinity of eddy #10. Between eddies #11 and #10 there is a net alongshore flow that sweeps floatables to Dungeness Spit (Ebbesmeyer et al., 1979). A third concentration occurred in segments #35 and #36 in the vicinity of the onshore flow between eddies #4 and #5. This comparison suggested that the larger spikes in the distribution of drifter recovery versus segment resulted from onshore flow associated with tidal eddies.

In Figure 2 the ovals circumscribe the approximate extent of the net currents that appear to circulate around the individual tidal eddies shown in Figure 3: the eddies in the northern areas of the eastern Strait are larger and more vigorous than those in the south. Assume that the strength and extent of eddies are proportionate to the flow of water into the eastern Strait. In other words, the eddies generated in the lee of the San Juan Islands and Victoria are proportional to the exchange of tidal waters between the eastern Strait and the Strait of Georgia, and that the eddies on the southern side are controlled by tidal exchange with Puget Sound.

To quantify this contention, consider the tidal prism, the volumes of water between mean high water and mean lower low water that feed the eastern Strait: Strait of Georgia, 25 cubic kilometers, or 76%; and Puget Sound, 8 cubic kilometers, or 24%. These percentages are within one standard error of those associated with the north-south asymmetry, namely 73% of recoveries on the northern shores of the eastern Strait, and 27% on the southern shores.

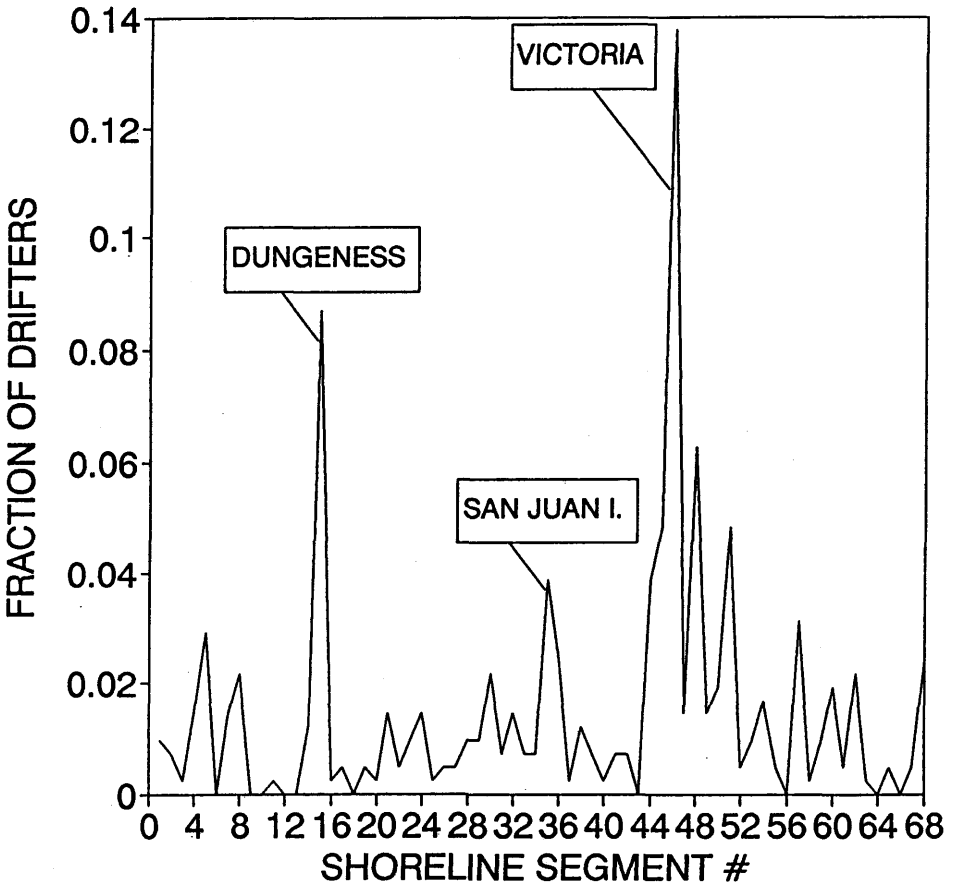

Figure 6.
***FRACTION OF TOTAL DRIFTER RECOVERIES** (active plus passive searches) found within the 68 segments of the Eastern Strait shoreline (see Fig. 2). Spikes account for most recoveries (Victoria, Dungeness, San Juan Island).*

Eddy Model — To further compare drifters with eddies, a simple algebraic model was developed. Assume that: (1) drifters are released in the center portion of a cylinder lined with a sequence of eddies (Fig. 8); (2) drifters are deposited along the edge of the cylinder wherever the flow has a component toward the cylinder; and (3) the drifters accumulate with normal probability between pairs of eddies where the flow is toward the cylinder.

In this model, no drifters are found along half of the cylinder's circumference because the flow is directed away from the cylinder between pairs of eddies. If the cylinder is segmented and cumulative drifter recoveries are tabulated using the same method as for the field observations, the curve shown in Figure 7 is obtained. Figure 7 also shows the result obtained if the drifter recoveries

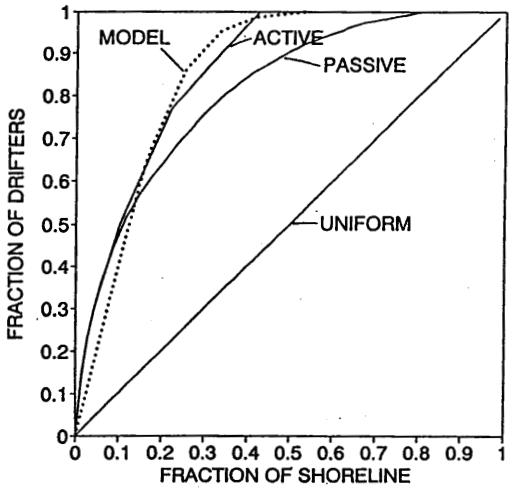

Figure 7.
CUMULATIVE FRACTION OF DRIFTERS RECOVERED ALONG THE SHORE OF THE EASTERN STRAIT: *ACTIVE, recoveries from active searches; PASSIVE, recoveries from passive searches; MODEL, result for the eddy model; and UNIFORM, distribution for drifters equally spread along the shore.*

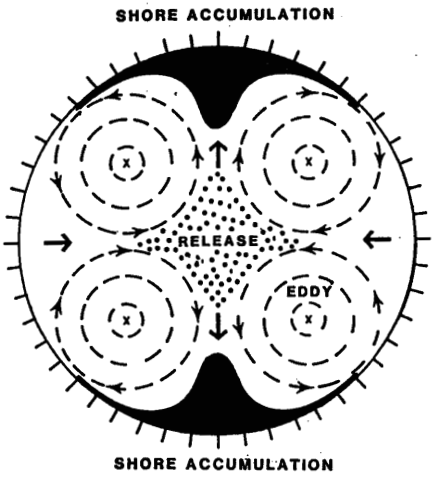

Figure 8.
DIAGRAM OF THE EDDY MODEL ILLUSTRATED *using four eddies (dashed) to transport floatables to shore. Ticks around cylinder circumference indicate segments used to compute results shown in Figure 7. Bell-shaped areas represent normal distributions where drifters accumulate after being released in the center of the cylinder (stippled area).*

are uniformly distributed around the cylinder.

Comparing the model and observations, it can be seen that drifters recovered during active searches more nearly coincide with the model than those from passive searches. Recoveries from both active and passive searches coincide more closely with the eddy model than the result from a uniform distribution.

Table 4.
***RECOVERIES OF DRIFTING MATERIALS IN THE EASTERN STRAIT OF JUAN DE FUCA** derived from seven data sets involving active and passive searches.*

		Percent recovered by area					
Data set	Total	North Shore (1)	South Shore (2)	Victoria (3)	San Juan Channel (4)	Dungeness Spit (5)	Total (3-5)
1. Active searches							
a. SS Pacific	17	82	18	41	6	6	53
b. Steamer Clallam	24	79	21	70	13	4	87
c. Drift sheets	19	68	32	26	16	5	47
Total	60						
Average		76	24	46	12	5	62
Standard error		3	3	13	2	<1	12
2. Passive searches							
a. Oregon coast	15	67	33	40	0	7	47
b. Georgia Strait	64	80	20	45	16	9	70
c. Puget Sound	138	60	40	41	18	13	72
d. Admiralty Inlet	137	72	28	47	15	12	74
Total	354						
Average		70	30	43	12	10	66
Standard error		4	4	2	4	1	6
3. Statistics for 7 data sets combined							
Total	414						
Average		73	27	44	12	8	64
Standard error		3	3	5	2	1	6

(3) Segments 45-56; (4) segments 30-38; (5) and segments 14-17 (Fig. 2).

DISCUSSION

The results suggest that the recoveries of drifters in the eastern Strait can be explained by strength and position of tidal eddies. Recoveries of individual releases are often said to be modified by winds. The releases reported herein represent a composite from many months, sites, and years. The agreement between recoveries and tidal characteristics further suggests that winds are of secondary importance to the recovery patterns in the eastern Strait.

The eastern Strait is a junction between several estuarine reaches (Haro Strait, Rosario Strait, Admiralty Inlet, western Strait of Juan de Fuca). This paper shows that tidal eddies can cause a significant degree of patchiness in the recovery of floatable materials. Since strong tidal eddies are present in a number of other junctions (off Alki Point, near The Narrows, and the five-way junction south of Dana Passage), we expect patchiness of onshore transport at many other locations in the Puget Sound region.

CONCLUSIONS

More than 16,000 drift objects were released primarily in the approaches to the eastern Strait of Juan de Fuca, including the Pacific Coast, Strait of Georgia, and Puget Sound. The 400 drifters found within the eastern Strait showed two striking patterns: approximately three quarters of the recoveries were made on the northern shores, versus one quarter on the southern shores; and approximately half of the recoveries were made in three specific locations totaling about one tenth of the Eastern Strait's shoreline (Victoria, San Juan Islands, Dungeness Spit). These results appear to be insensitive to the type of drifter, or to whether the drifters are actively sought out or are simply found by beachwalkers happening upon them.

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CONCENTRATIONS AND AGES OF CONSERVATIVE POLLUTANTS IN PUGET SOUND

E.D. Cokelet[1], R.J. Stewart[2] and C.C. Ebbesmeyer[3]

INTRODUCTION

Predicting the fate of pollutants in Puget Sound depends upon an adequate understanding of the movement of water through the estuary. This is especially true of conservative substances, defined as those that move with the water, remain inert after entry, and eventually flow out to sea. The objectives of this research are to deduce the long-term mean circulation within the Strait of Juan de Fuca and Puget Sound and to predict the concentrations and timescales of conservative pollutants or tracers introduced there. Past efforts have been devoted to oceanographic circulation studies, but until now these have not been combined into a single, regional, predictive model.

The work reported here represents the culmination of that presented at the first Meeting on Puget Sound Research (Cokelet et al., 1988). Techniques have been refined, and error analyses have shown the effects of temporal variability on the mean state of the system and on related predictions.

CIRCULATION

The estuarine system is composed of a series of deep, stratified reaches where the long-term mean circulation is predominantly two-layered advection (i.e. longitudinal translation with negligible mixing) in the form of lower-layer, landward flow and upper-layer, seaward flow (Figures 1 and 2). The reaches are separated by mixing zones in which rivers enter and tidal currents accelerate owing to constricting shallow sills.

Multi-year observations of salinities and currents (Figure 1) within the reaches enabled us to deduce the mean flow through conservation of mass principles applied to salt and fresh water (Cokelet et al., 1990a, b). Runoff into the mixing zones generally decreases as one moves landward along the main axis of the estuary from the outer Strait (layers 1-2, Figure 3a) to the southern Sound (layers 11-12). In each reach the water flowing landward is saltier than that flowing seaward (Figure 3b). Both salinities decrease as one moves up the estuary except in Colvos Passage (layer 8). The seaward flow there is saltier

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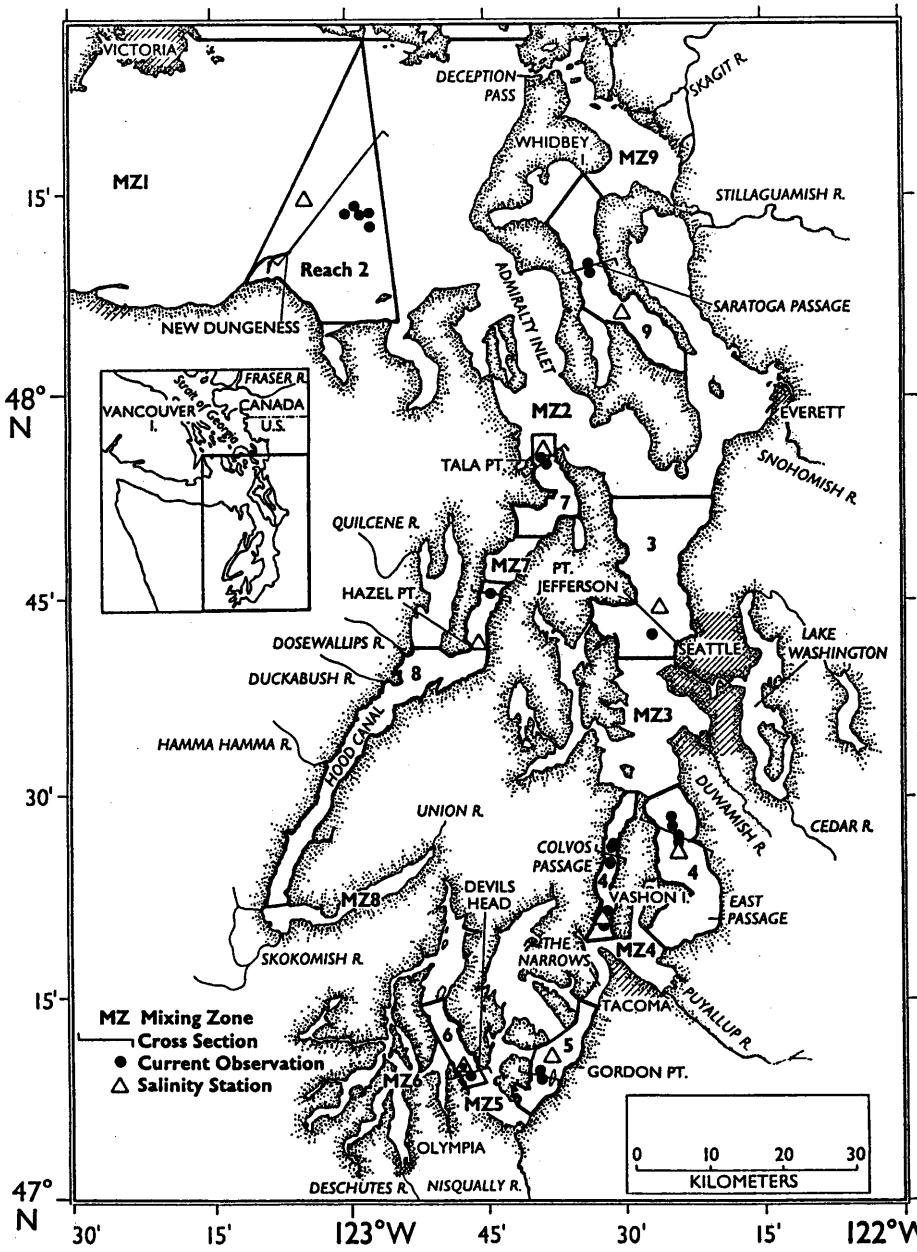

Figure 1.
THE REACHES (BOLD OUTLINES) AND MIXING ZONES (MZ) OF THE STRAIT OF JUAN DE FUCA/PUGET SOUND ESTUARY (COKELET ET AL., 1990A, B). *Reach 1 (not shown) occupies the outer Strait. Sites of current and salinity observations are shown.*

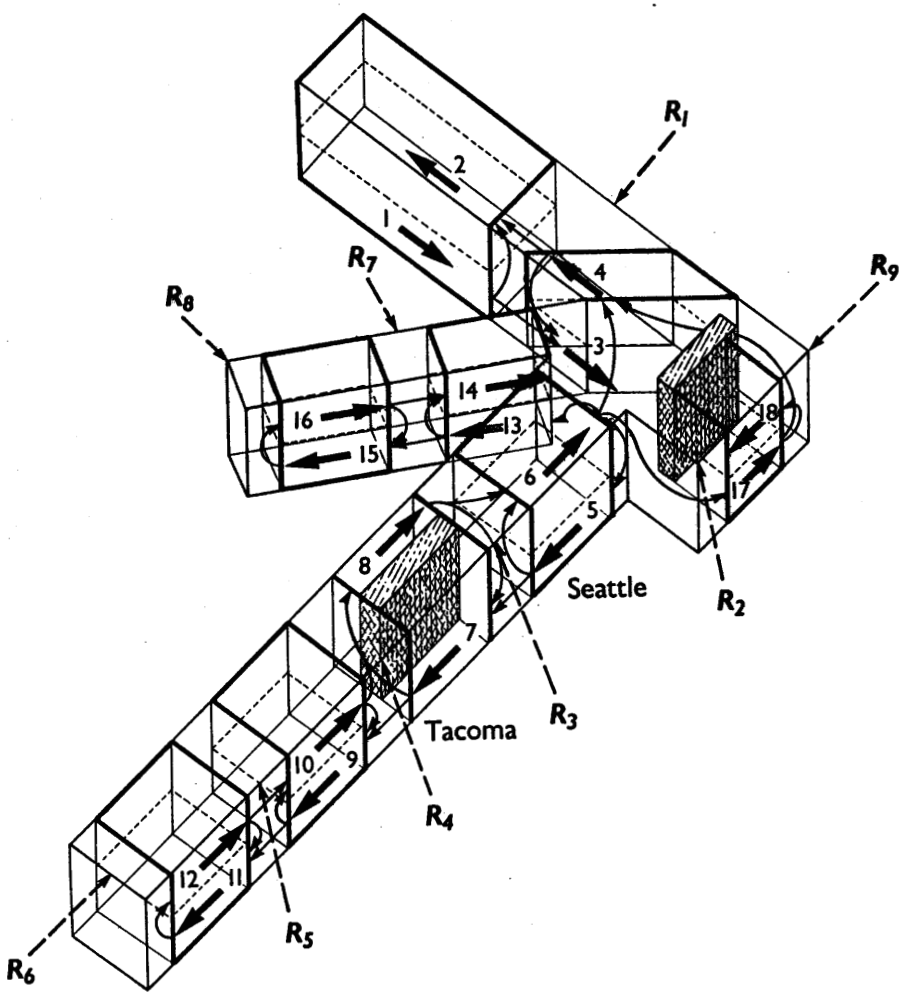

Figure 2.
SCHEMATIC DIAGRAM OF THE PUGET SOUND REFLUX MODEL (COKELET ET AL., 1990C). *The layers are numbered such that layers 2i-1 and 2i correspond to reach i of Figure 1. Each river runoff (R) index corresponds to the mixing zone that the river enters and to the reach immediately seaward. Bold arrows denote two-layered reach flows, and thin arrows denote the efflux/reflux coefficients in the mixing zones. Not all arrows are shown in mixing zone 2.*

than that on either side because it extends to the sea floor. The two-layered flow in this reach is juxtaposed with Colvos Passage flowing north, and East Passage (layer 7) flowing south, giving a clockwise mean circulation around Vashon Island. There is more transport around Vashon Island than in the neighboring reaches (layers 5-6 to the north and layers 9-10 to the south, Figure 3c). Except for this, the volume transports decrease from the mouth of the Strait (layers 1-2) to the southern Sound (layers 11-12).

REFLUXING

The two-layered flows enter the turbulent mixing zones and intermingle. Each inflow is apportioned into a reflux fraction that recirculates into its original reach and efflux fractions that enter other reaches (Figure 2). These fractions have been related directly to pollutant retention (Cokelet et al., 1985). Although refluxing occurs to some extent in every mixing zone, some examples are particularly important (Cokelet et al., 1990c). About half (49%) of Colvos Passage's transport refluxes into East Passage because the flow around Vashon Island is stronger than that in the neighboring reaches. In Admiralty Inlet 31% of the seaward-flowing water from off Point Jefferson (layer 6) returns landward in lower layer 5. In aggregate, 52% of the water entering Admiralty Inlet from Puget Sound layers recirculates into other Puget Sound layers. (These values are slightly different from those reported earlier [Cokelet et al., 1988] because a different method was used to compute the under-determined reflux coefficients within multiple-junction mixing zones. See Cokelet, et al. [1990c] for details.)

POLLUTANT CONCENTRATIONS

Knowledge of the transports and reflux coefficients provides a foundation for predicting the concentration of conservative pollutants injected steadily into each reach layer from a source assumed to be vertically and laterally uniform. Inputs into any combination of the 18 major layers and 9 rivers of the Strait and Sound (Figure 2) are considered. Figure 4 contrasts the results of four separate injections of 1 kg/s of pollutant into the upstream ends of layers 5-8 (Figure 2) nearest the population centers of Puget Sound (Cokelet et al., 1990d). Injection into landward-flowing layer 5 off Point Jefferson (Figure 4a) gives concentrations of about 115 parts per billion (ppb) in the main basin and southern Sound (layers 5-12). A similar input into seaward-flowing layer 6 (Figure 4b) leads to about 47 ppb in the layers to landward. This is less than a layer-5 injection since layer 6 flows seaward, thus carrying pollutants away initially. However, refluxing in Admiralty Inlet leads to their introduction into layer 5 where they flow landward. An input into East Passage (layer 7) gives results nearly identical to layer-5 injection (Figure 4c) since 100% of layer 5 flows directly into layer 7 with no refluxing into layer 6 in mixing zone 3. A layer-8

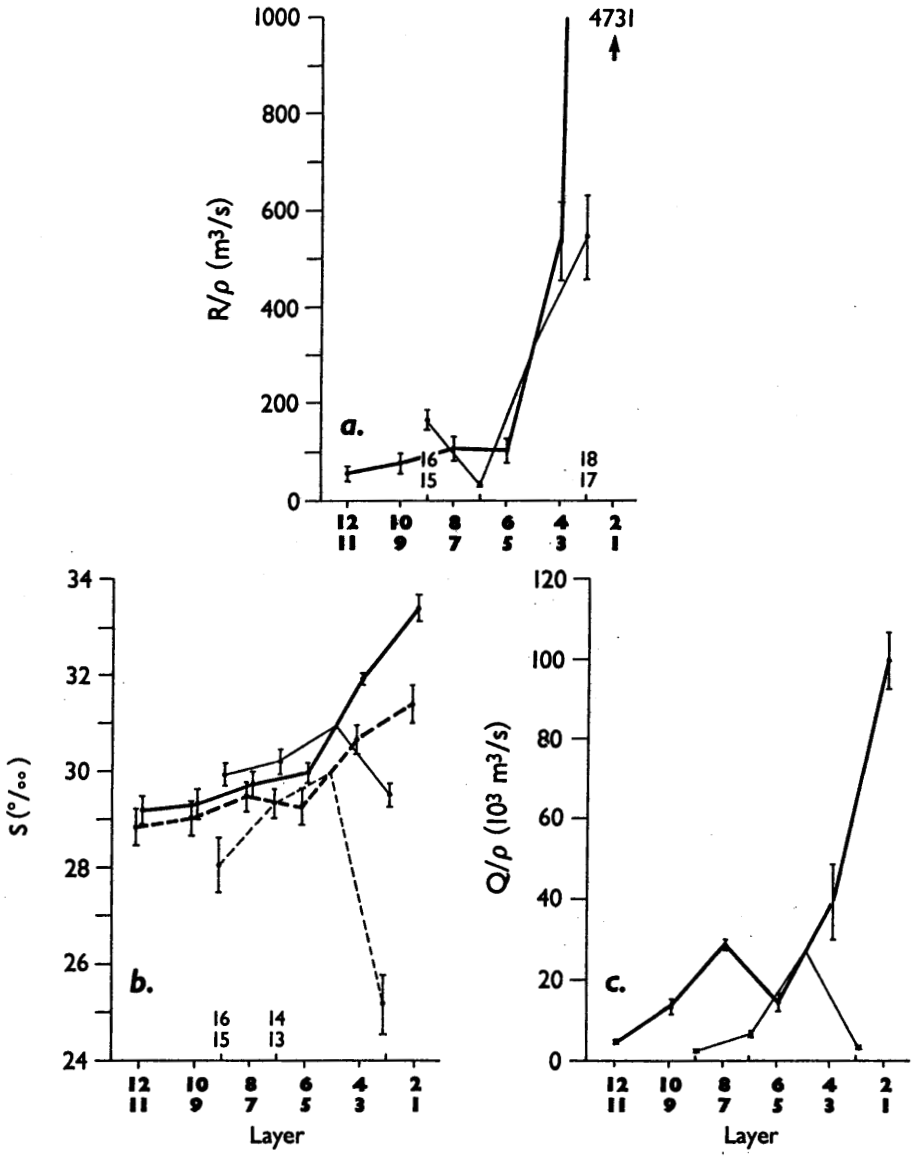

Figure 3.
THE MULTI-YEAR AVERAGED (A) RUNOFF *(R/ρ, ρ = mean fluid density), (b) flux-weighted layer salinities (S), and (c) volume transports (Q/ρ) plotted as functions of position along the estuary (Cokelet et al., 1990d). Bold solid and dashed lines denote the landward- and seaward-flowing layers, respectively, along the main axis. Thin lines denote similar layers in the side reaches of Hood Canal and Saratoga Passage. Error bars denote the standard error of the mean which is due to temporal variability. The seaward-flowing volume transports are not shown because they differ little from those flowing landward.*

injection in Colvos Passage leads to about 80 ppb concentrations in the southern Sound. This is lower than a layer-7 injection because about half of Colvos' flow effluxes seaward into layer 6, but it is higher than a layer-6 injection because the remaining half of Colvos' flow refluxes landward into East Passage layer 7. (These predictions differ somewhat from those of Cokelet et al. [1988] owing to the different method of calculating the reflux coefficients.)

POLLUTANT AGES

Timescales of their motion are useful to determine how long it will take pollutants to move from place to place. One such timescale for the steady estuarine system is "mean age," defined as the average age of all conservative pollutant particles injected in one layer and observed at the downstream end of another. It is a function of the input and observation sites and can be calculated from a knowledge of the circulation, refluxing and pollutant concentrations (Cokelet and Stewart, 1985). For the Strait of Juan de Fuca/Puget Sound estuary, model results show that the mean age can vary from 14 days to 277 days. The lowest value is for pollutants injected into layer 2 of the outer Strait and passing directly out to sea. The highest value is for an input into lower layer 15 of Hood Canal and an observation in upper layer 12 of the southern Sound (Cokelet et al., 1990d). (These values exceed those reported previously (Cokelet et al., 1988) because the present estimates include the time spent in the mixing zones.)

If the observation site is fixed at the seaward end of layer 2 where substances are assumed to leave the estuary forever, then the mean age at this site becomes the average "age-leaving" (τ_2). This is sometimes called the "lifespan", "residence time" or "flushing time." It is equivalent to the ratio of the total mass of tracer within the estuary to its flux leaving. For fresh water with several sources the average age-leaving is 67 days, but this is dominated by the Fraser River that enters mixing zone 1 near the estuary's mouth. For other input sites the values can be very different, ranging from 14 days for inputs into seaward-flowing layer 2 of the outer Strait to 221 days for inputs into the landward-flowing layer 12 of the southern Sound (Figure 5a).

Another useful timescale is the average age of pollutants within the estuary which is defined to be the mass-weighted sum of the ages within each reach and mixing zone. For a given estuary this "age-within" (Θ) depends upon where the pollutant is injected. It varies between 7 and 156 days for single-source inputs into the Strait and Sound (Figure 5b). The ratio of the age-leaving to the age-within distinguishes three types of circulation conditions. For a bypassing system ($\tau_2/\Theta \rightarrow 0$) most of the pollutant leaves the estuary quickly, but that remaining spends a relatively long time circulating through

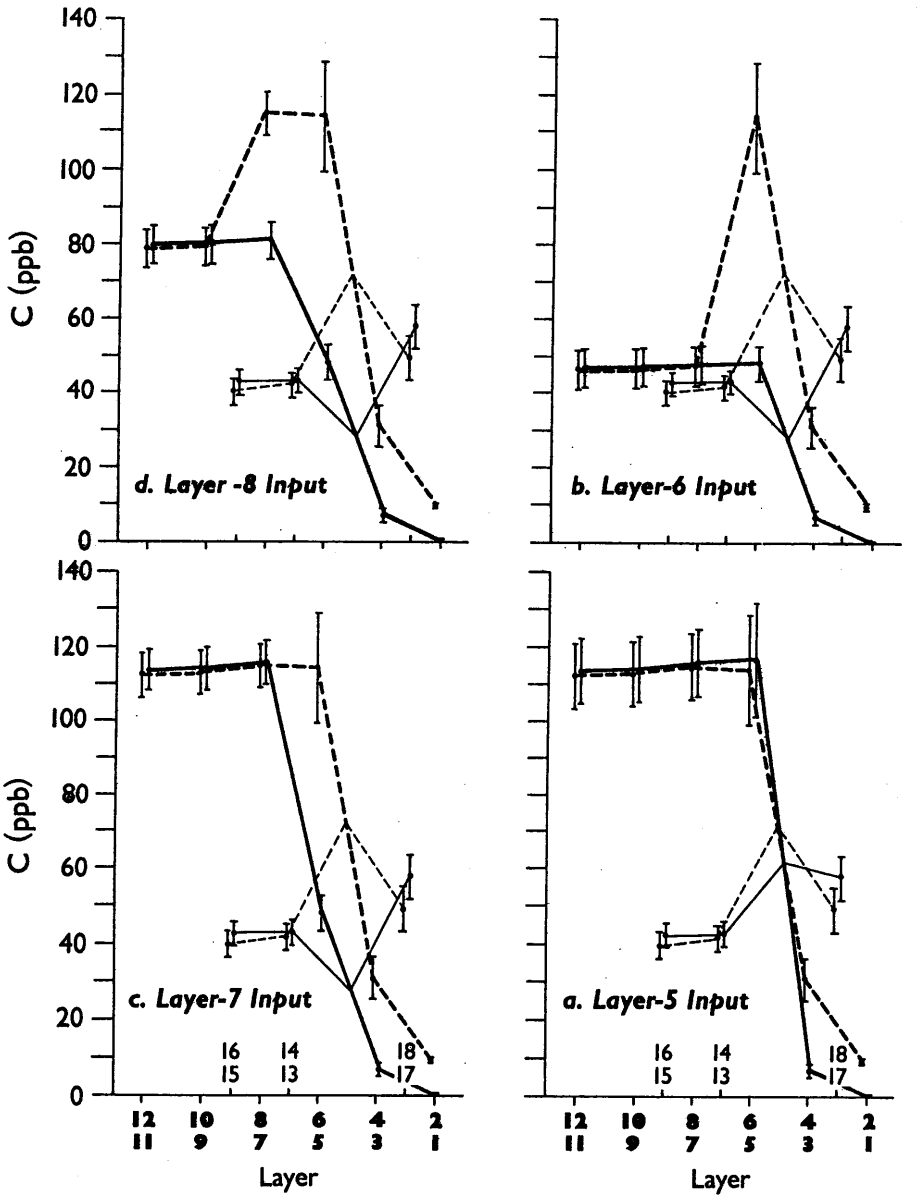

Figure 4.
***CONSERVATIVE POLLUTANT CONCENTRATIONS** (C) plotted as functions of position along the estuary (Cokelet et al., 1990d). The predicted values result from 1 kg/s unit inputs into the upstream ends of (a) landward-flowing layer 5 off Point Jefferson, (b) seaward-flowing layer 6 off Point Jefferson, (c) landward-flowing layer 7 in East Passage, and (d) seaward-flowing layer 8 in Colvos Passage. See Figure 3 for an explanation of line types.*

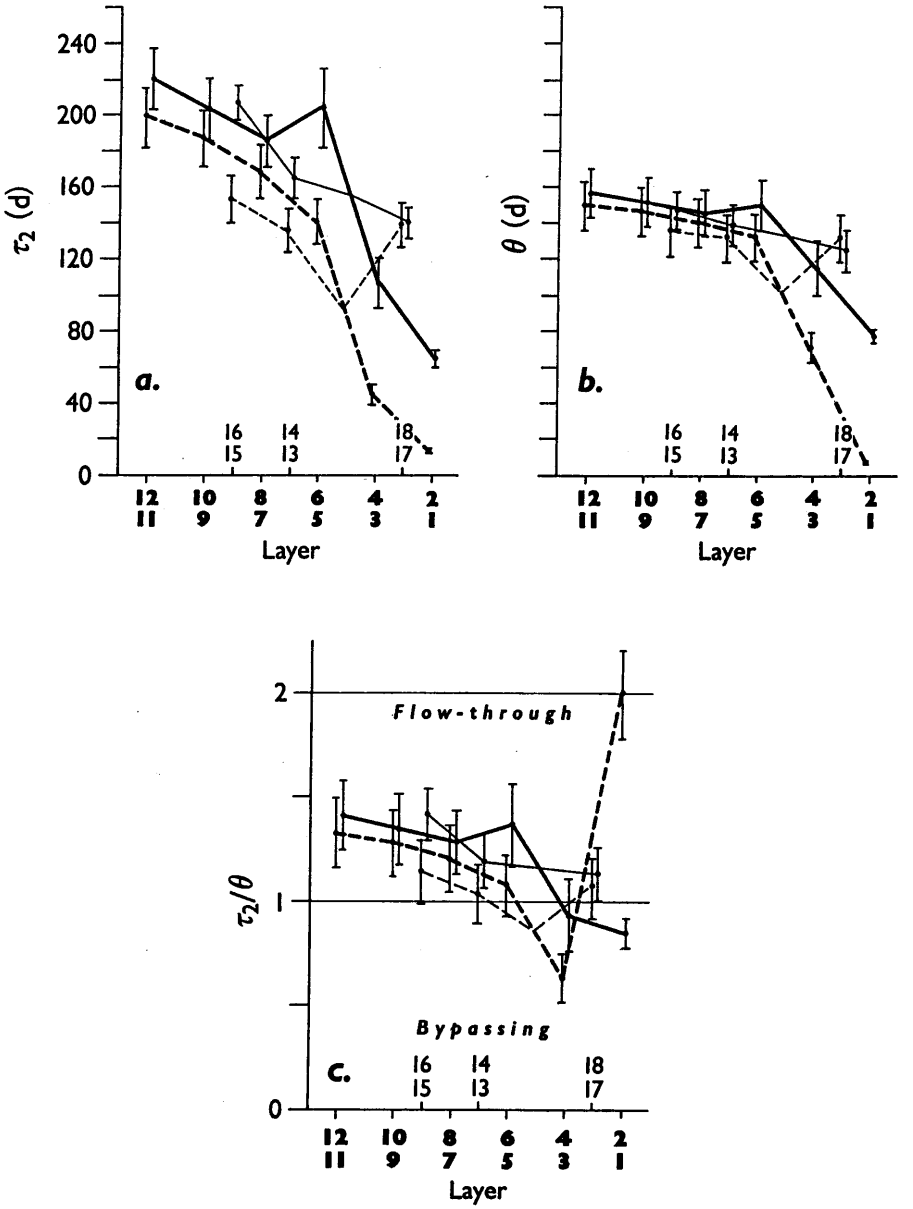

Figure 5.
THE MEAN AGE OF CONSERVATIVE POLLUTANTS *(a) leaving (τ_2) the outer Strait of Juan de Fuca and (b) within (θ) the Strait and Sound and (c) their ratio plotted as functions of their site of injection (Cokelet et al., 1990d). See Figure 3 for an explanation of line types.*

it. In a well-mixed estuary the age-leaving equals the age-within ($\tau_2/\Theta = 1$). For a flow-through system ($\tau_2/\Theta \rightarrow 2$) pollutant passes through the estuary as if on a conveyor belt. Inputs into layers 1, 3 and 4 of the Strait tend toward a bypassing condition ($0 \leq \tau_2/\Theta \leq 1$, Figure 5c). However, inputs into Puget Sound (layers 5-12) give more of a flow-through response ($1 < \tau_2/\Theta < 2$, Figure 5c), but the pure flow-through limit is never achieved due to refluxing.

CONCLUSIONS

The Puget Sound Reflux Model provides a useful first tool for managing Puget Sound as an entire system in which the combined, long-term pollutant loadings and timescales can be examined in a unified manner. A personal computer version of the model is under development through funding from the Puget Sound Estuary Program under the auspices of the U.S. Environmental Protection Agency, the Washington Department of Ecology and the Puget Sound Water Quality Authority.

ACKNOWLEDGEMENTS

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THE BIOCHEMISTRY OF OXYGEN AND NUTRIENTS IN HOOD CANAL

Herbert C. Curl, Jr. and Anthony J. Paulson[1]

INTRODUCTION

Hood Canal has been chosen as a model system to explore the general relationships among nutrient loadings, recycling processes and the potential for hypoxia and anoxia in a fjord-like estuary. In addition, Hood Canal itself is undergoing significant development and parts already are ecologically stressed. At the southern-most end, Lynch Cove, on which this paper will focus, receives raw sewage from failed septic tanks and is the site of future commercial development. Thus it is important that we understand the functioning of this still relatively unspoiled estuary.

Although equal in length to Puget Sound, Hood Canal's morphometry is less complex and it receives less freshwater input. However, freshwater is delivered primarily near the head of the estuary almost year around, producing a lens of brackish water and a shallow (5-10 m) pycnocline. This persistent stratification, coupled with seasonal nutrient input from oceanic sources and high levels of biological production in the coves and embayments, can result in hypoxia in deeper water, extending as far north as Dabob Bay, and anoxia in a thin tongue just beneath the pycnocline, extending as far north as Hoodsport in late summer. This regimen can be seen in data obtained in the 1950s and 1960s by the University of Washington (Collias et al., 1974), by Oregon State University in the 1970s (Curl, unpublished data), and by NOAA in 1986 (Paulson et al., 1991).

To the superficial observer the circulation appears vigorous, especially over the sill near the Hood Canal Bridge and at the Great Bend at the southern end, because of strong tidal currents of up to 50 cm per second. However, residual currents are weak, advective transport is relatively slow, and there is little vertical mixing. At present, the major nutrients are supplied by renewal of deeper water supplied by periodic intrusions of ocean water over the sill. The data presented here were obtained in late August, 1986, after a period of nearly four months during which there were probably no intrusion events (Mofjeld, 1990, personal communication). Thus, the distributions seen are the result of summer-time biological production and subsequent recycling processes.

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DENSITY AND OXYGEN DISTRIBUTIONS

Water of highest density (23.4 σ_t) lay well outside the sill and in the deepest portion of Hood Canal (Fig. 1). The surface fresher water layer extended to the sill with a pycnocline at 10 m. Oxygen isopleths under the pycnocline slope toward the bottom from south to north and are suggestive of major depletion during the summer (Fig. 2). The minimum values are 30% of saturation and the volume of hypoxic water is much greater than any seen in the previous three decades; the lowest oxygen values are always found at the bottom between Hoodsport and Lynch Cove. A variation on this distribution, which was observed in September 1974 (Curl, unpublished data), is the existence of an hypoxic/anoxic tongue extending from the south directly under the pycnocline. Unlike many fjords with shallow sills, Hood Canal probably cannot go anoxic in its deep basin due to periodic renewals of bottom water by intrusions from the Strait of Juan de Fuca.

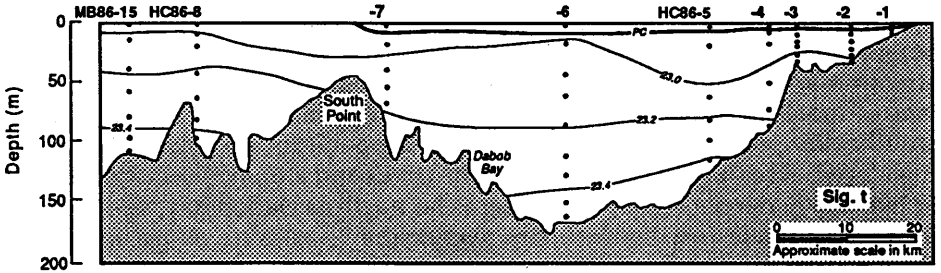

Figure 1.
DISTRIBUTION OF DENSITY (σ_t) IN HOOD CANAL, AUGUST 1986. *PC near the surface indicates depth of the pycnocline.*

NUTRIENTS

Phosphorus

The highest value for particulate phosphorus lies directly under the pycnocline (Fig. 3) and represents settling and northward advection of recently produced particulate organic matter (POM). Particulate organic phosphorus in POM that has already settled to the bottom apparently has been released as dissolved phosphorus (Fig. 4). (Phosphorus is readily remineralized from organic matter on a time scale of weeks.) Phosphate was depleted in the surface layer as far north as the Duckabush River. The distribution of stations was too coarse to reveal any local land sources of phosphate but they undoubtedly exist; the Tahuya River should be examined, in particular.

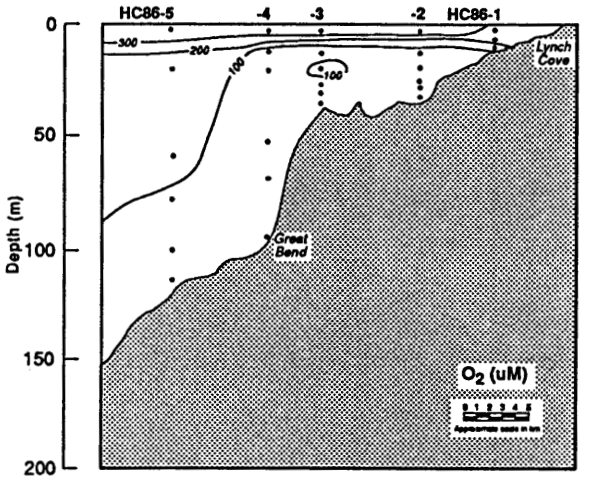

Figure 2.
DISTRIBUTION OF OXYGEN (μM O_2) IN SOUTHERN HOOD CANAL.

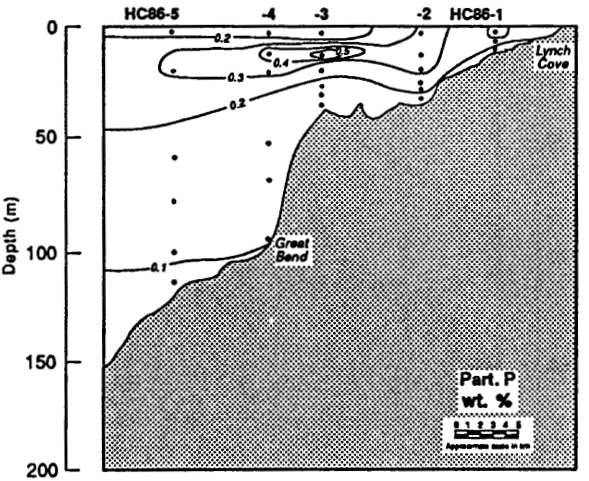

Figure 3.
DISTRIBUTION OF PARTICULATE PHOSPHORUS (WEIGHT PERCENT P) IN SOUTHERN HOOD CANAL. *Particulate P acts as a surrogate for biologically produced organic matter.*

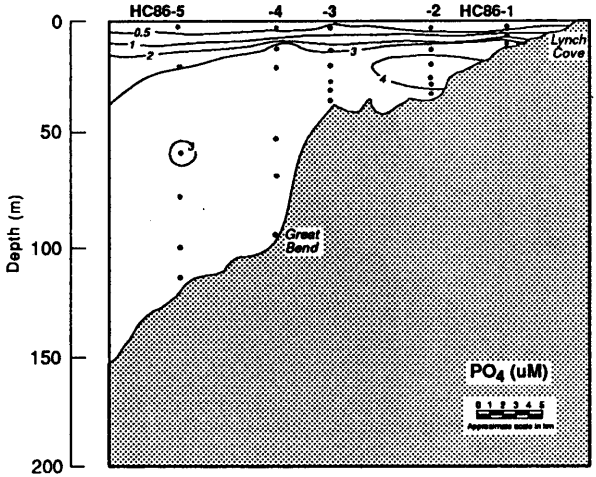

Figure 4.
DISTRIBUTION OF PHOSPHATE (μM PO_4).

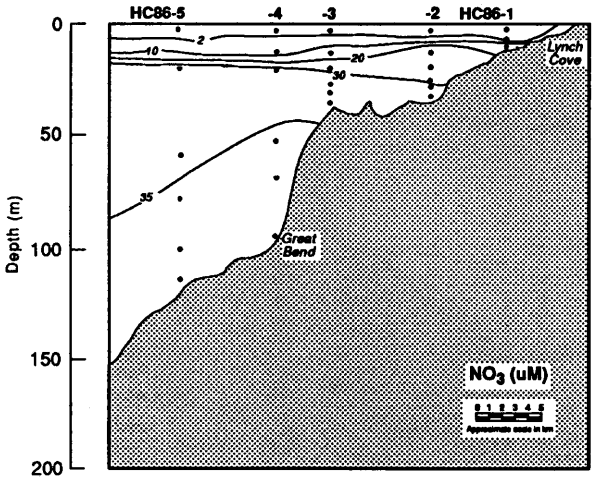

Figure 5.
DISTRIBUTION OF NITRATE (μM NO_3).

Nitrogen

The distribution of nitrogen species is one of the most interesting aspects of the chemical oceanography of Hood Canal. In 1968 the highest concentration of nitrate (35 μM NO_3) occurred near bottom between the Great Bend and Dabob Bay (Fig. 5). This value is 15 μM in excess of the seawater source outside the sill (20 μM NO_3). If we assume that excess nitrate is regenerated from oxidized organic matter having an original Redfield ratio of 106 C:16 N, then the apparent oxygen utilization (AOU) of 200 μM in the deep water of Hood Canal should lead to the regeneration of 23.2 μM of NO_3, (Riley and Chester, 1971) which is considerably greater than the 15 μM NO_3 excess in the deep water. One possible explanation for the difference is consumption of regenerated nitrate by chemoautotrophs.

Cruises in January and September 1974 revealed high levels of urea and amino acids near bottom in Lynch Cove. A tongue of water extended seaward near bottom in and below the pycnocline with the highest values of NH_3 (6 μM) at the seaward end. In 1986 a maximum of NH_3 was found in the same location (Fig. 6) and was indicative of early nitrogen regeneration of sedimented POM. From this locus a broad tongue of nitrite-enriched water extended as far as Hoodsport, with a near-bottom maximum of 0.5 μM (Fig. 7). The shape of the tongue suggests advective processes at work, much in the manner of the 1974 distributions. That we were observing an event characteristic of the sedimentation of a recent large plankton bloom is indicated by the following suggested sequence: 1) sinking of nutrient depleted cells (low nutrients in surface layer, mid-depth maximum of particulate P); 2) advection landward of organic debris and release of labile P (landward displacement of bottom PO_4 maximum); 3) continued landward advection of organic matter and release of regenerated N (seaward displacement of NH_3 maximum); 4) recent conversion of an advected plume of NH_3 to NO_2 (large volume of ephemeral NO_2); and 5) the lack of a distal NO_3 maximum observed on other occasions.

CONCLUSIONS

The southern end of Hood Canal is naturally biologically productive (Barlow, 1958). The oxidation of organic matter which settles to the bottom leads to large volumes of hypoxic water. Alternatively, under strong stratification, organic matter may settle close to the point of origin and the subsequent oxidative and advective processes lead to a subsurface hypoxic/anoxic layer. It is this relatively shallow layer that may lead to periodic fish kills. Although the main basin of Hood Canal would require considerably increased inputs of organic matter to go anoxic since oxygen is renewed by intrusions of oxygenated water over the deep sill, deep oxygen concentrations are frequently less than 50% of saturation and may go as low as 10% in Lynch Cove. The persistent, shallow, mixed layer and lack of light limitation in the summer time

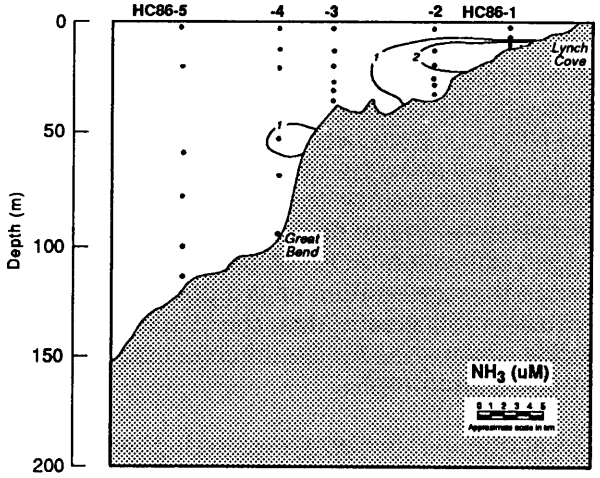

Figure 6.
DISTRIBUTION OF AMMONIA (μM NH_3).

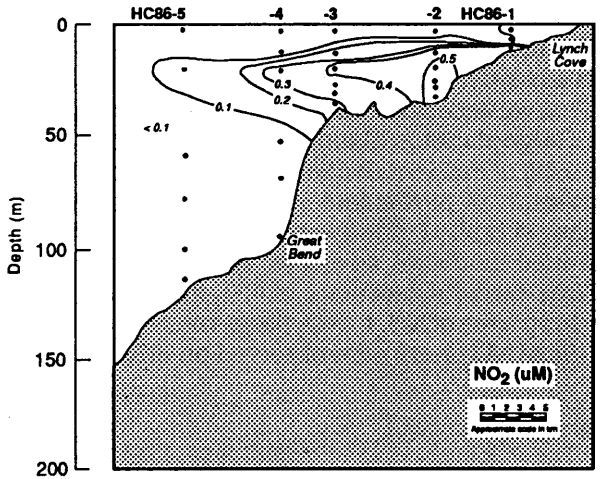

Figure 7.
DISTRIBUTION OF NITRITE (μM NO_2).

suggest that increasing eutrophication could seriously affect the southern portion of Hood Canal. Increasing development and discharge of secondary effluent with its readily available nutrients into water shallower than 50 m would probably increase the severity and duration of fish kills, but could also cause other deleterious effects such as altered food chains and toxic algal blooms.

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BIOGEOCHEMISTRY OF TRACE METALS IN HOOD CANAL

Anthony J. Paulson and Herbert C. Curl, Jr. [1]

INTRODUCTION

Hood Canal is a classic fjord with sluggish circulation and a stratified water column. When the water column stratifies in the spring and summer, nutrients are depleted in the surface by biological growth and regenerated in the bottom waters due to the decomposition of settling surface marine organic matter (Curl and Paulson, 1991). Concurrent with the regeneration of nutrients, oxygen is depleted in the bottom waters. The depletion of oxygen can affect the distribution of the trace metals that have sensitive oxidative-reductive (red-ox) cycles. In a classic fjord with a strong vertical oxygen gradient (Fig. 1), soluble reduced species (i.e. Fe^{+2} and Mn^{+2}) are produced in low-oxygen bottom layer waters or in the sediments. These ions then diffuse through the oxic-anoxic boundary to the overlaying oxic layer where they are oxidized to their insoluble forms (Fe_2O_3 and MnO_2) which settle vertically back into the anoxic layer (Emerson, 1980). Redox sensitive species will continuously cycle between their soluble reduced species and their insoluble oxidized species without settling completely to the bottom sediments. In the vicinity of the Great Bend, where a horizontal oxygen gradient can occur (Fig. 1), the insoluble oxidized species may be able to settle to the sediments before being reduced. Since the Puget Sound Ambient Monitoring Program found elevated concentrations of three redox sensitive trace metals (Fe, Cr and V) at their station near the Great Bend, we examined water column dissolved and particulate Fe and Mn distributions during August 1986 to determine if the above elevations could have been a result of water column chemistry. Total suspended matter (TSM) and particulate aluminum concentrations aided in the interpretation of the Fe and Mn data.

METHODS

Water samples were collected in modified Teflon-coated Go-Flo™ bottles attached to a rosette sampler (particulate trace metal samples) or a Kevlar hydroline (dissolved trace metal samples). All filtration apparatus were acid-cleaned and rinsed with Milli-Q™ water. All operations open to the atmosphere were performed in a Class-100 laminar flow hood. Particulates were collected on acid-cleaned 37 mm 0.4 µm Nuclepore filters. Dissolved samples were collected in acid-cleaned high-density polyethylene (HDPE) after filtra-

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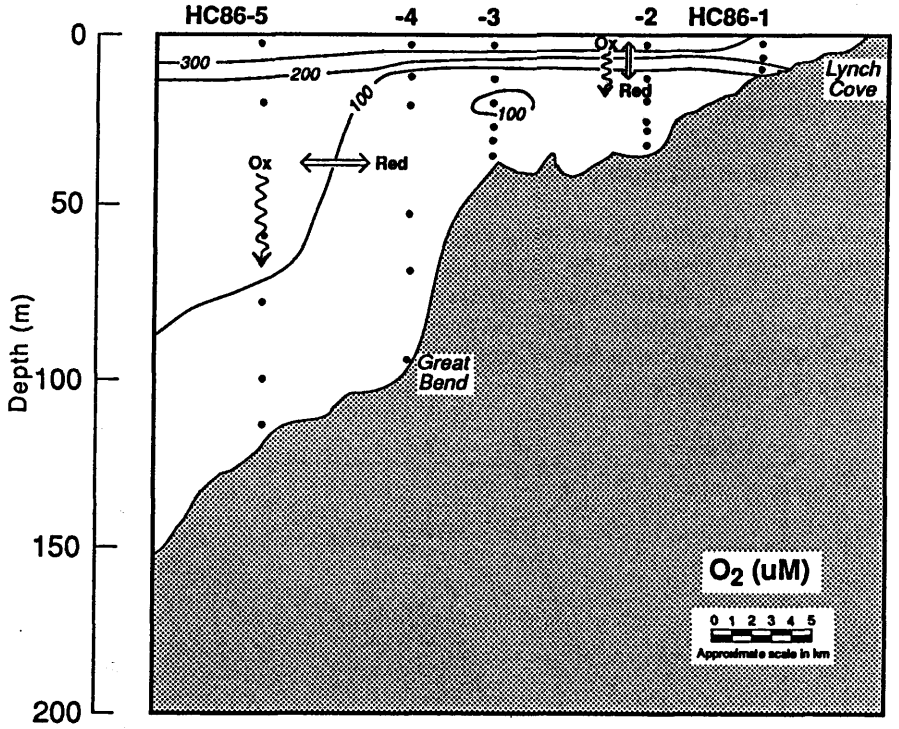

Figure 1.
***OXYGEN DISTRIBUTION IN HOOD CANAL** and reductive (Red)-oxidative(Ox) cycling with a vertical oxygen gradient (right) and a horizonal oxygen gradient (left). Mixing of dissolved reduced species (⇔) and settling of oxidized particulate forms (⇩).*

tion through acid-cleaned 50 mm 0.2 μm Nuclepore filters held in a Savillex™ filter holder and preserved with Seastar™ high-purity HNO_3. Dissolved trace metals were analyzed by the graphite furnace atomic absorption spectrometry following pre-concentration by the Chelex-100™ method of Paulson (1986). Total suspended matter (TSM) was determined gravimetrically on Cahn electrobalances while particulate trace metals were determined by the X-ray primary- and secondary-emission spectrometry using a Kevex 770 X-ray energy spectrometer. The raw data and QA/QC data are found in Paulson et al. (in prep.).

RESULTS AND DISCUSSION

The total suspended matter (TSM) distribution exhibited maximum concentrations in the surface layer from the Great Bend to Lynch Cove and near the bottom to the east of the Great Bend as the depth shallows (sta. HC86-3 in Fig. 1). The Al concentration of particles were low compared to riverine sediments

(Feely et al., 1986) and increased towards the bottom. The high TSM and low Al concentrations in the surface waters were consistent with the high biological production inferred from the nutrient distributions (Curl and Paulson, 1991). Likewise, the high TSM and high Al concentrations found near the bottom were consistent with bottom sediments with a high aluminosilicate content being resuspended into the water column.

Dissolved Fe concentrations were highest in Lynch Cove (>30 nM) and decrease seaward towards the main basin of Puget Sound (>10 nM). The dissolved Fe concentrations in Lynch Cove were low compared to anoxic waters, which is consistent with the presence of >50 μM dissolved oxygen in bottom waters. Fe concentrations on particles were low and decreased towards the bottom (Fig. 2).

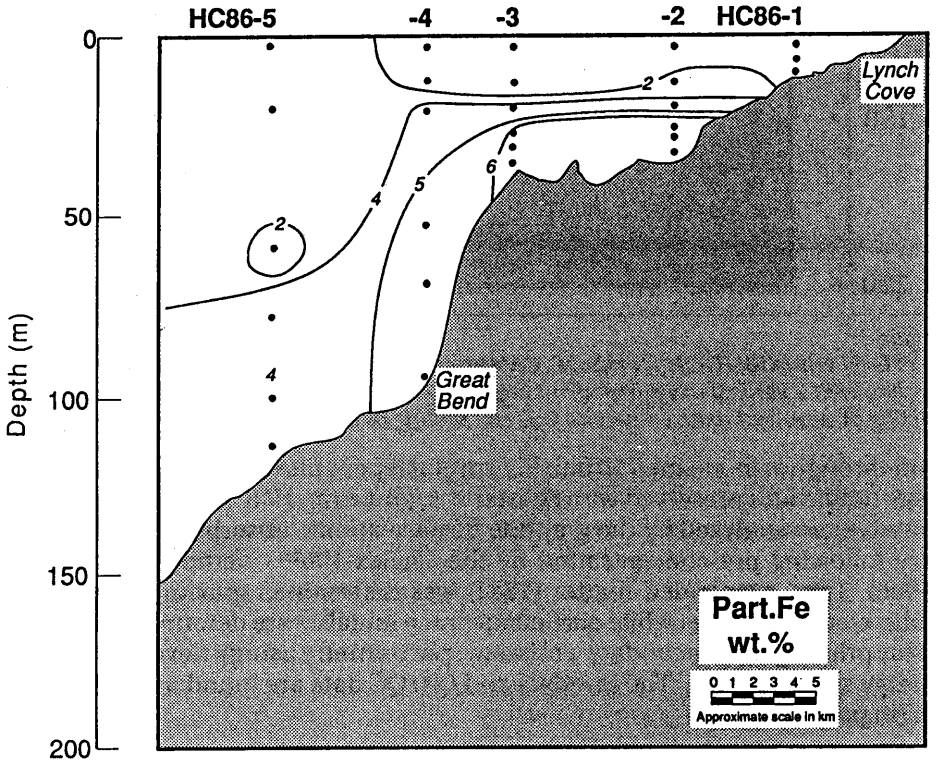

Figure 2.
DISTRIBUTION OF PARTICULATE FE OF HOOD CANAL SUSPENDED MATTER (in wt%).

Since most particulate Fe in estuaries is associated with aluminosilicates, the increases in Fe concentrations near the bottom were probably a result of the increasing aluminosilicate content of the particles. In order to deconvolute a geochemical signal from changes in particulate composition, a parameter called excess particulate Fe was calculated according to the following:

$$\{\text{Ex. Part. Fe}\} = \{\text{Part. Fe}\} - 0.82 * \{\text{Part. Al}\}$$

where { } is the metal concentration of the particles in wt.% and 0.82 is the Fe/Al ratio of Skokomish River suspended matter (Paulson et al., in prep.). Excess particulate Fe exhibited a maximum above the shallows east of the Great Bend (Fig. 3) in the same vicinity of the TSM maximum. Since the concentrations of excess particulate Fe (in μ moles/l) increased in the high TSM region as the sediment bottom was approached, the primary source of excess particulate Fe was probably resuspended bottom sediment enriched in Fe.

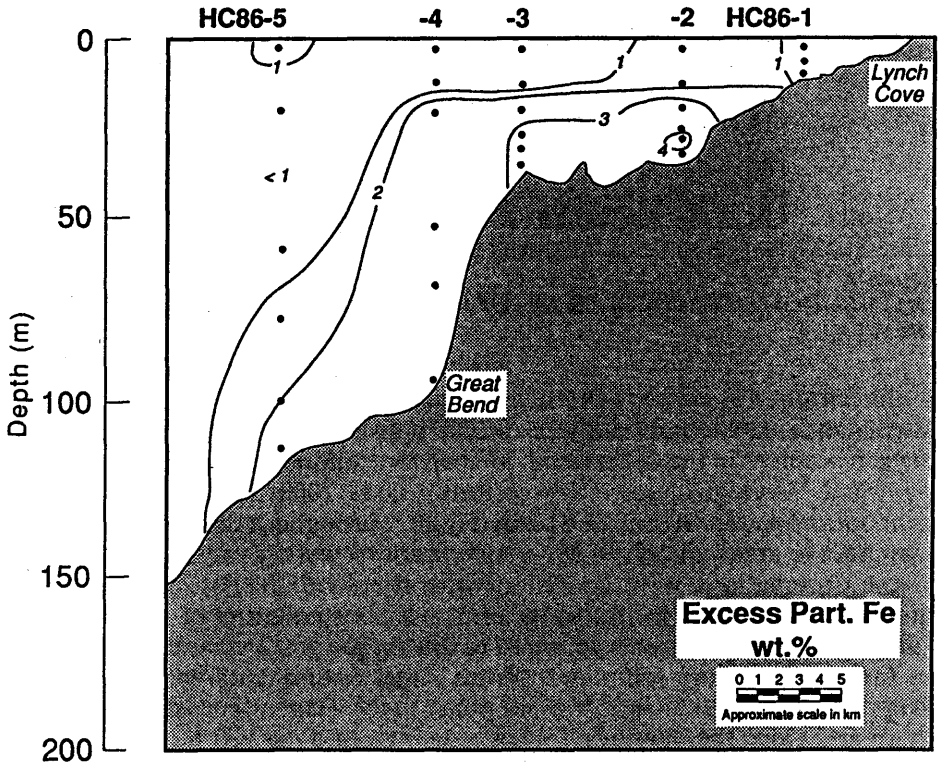

Figure 3.
***DISTRIBUTION OF EXCESS PARTICULATE FE OF HOOD CANAL SUSPENDED MATTER** (in wt%).*

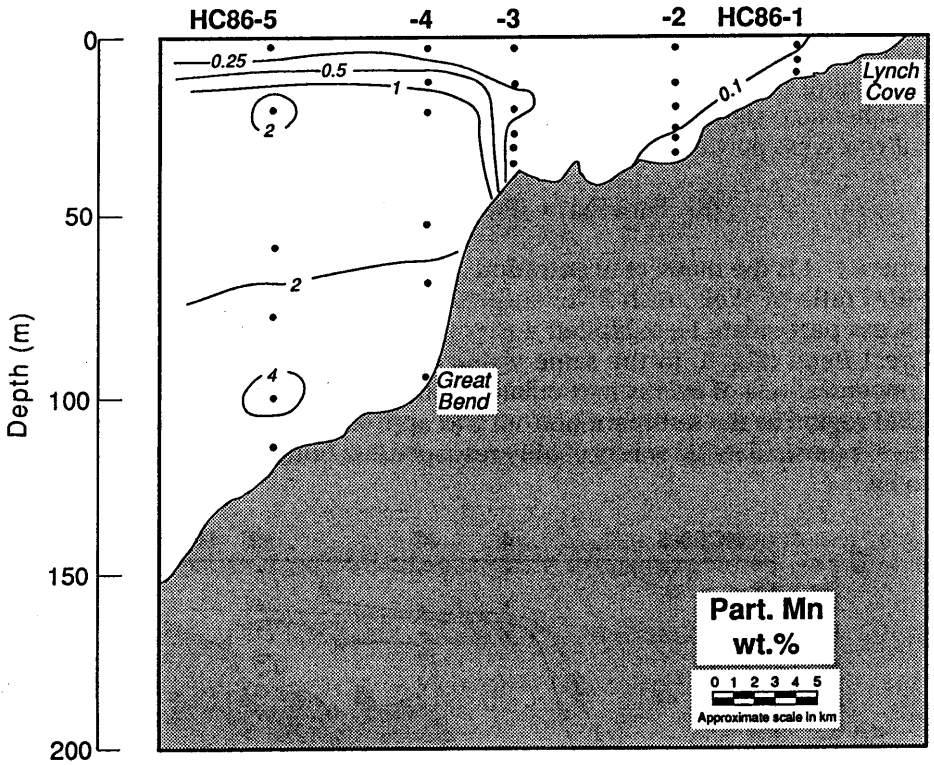

Figure 4.
DISTRIBUTION OF PARTICULATE MN OF HOOD CANAL SUSPENDED MATTER (IN WT%).

In the bottom waters near Lynch Cove (Fig. 4), the lowest Mn concentration of particulates were found (<0.1 wt% or 1000 ppm). In the area of the horizontal oxygen gradient in the Great Bend, Mn concentrations on particles increased by 40 fold. Very high dissolved Mn concentrations (1000 nM) were found in the near bottom waters of the Great Bend (Fig. 5). Throughout the Great Bend and Lynch Cove areas, dissolved Mn concentrations were greater than 100 nM. These observations were consistent with the solubilization of Mn to the dissolved Mn^{+2} form in the water and sediment columns of Lynch Cove. Dissolved Mn diffuses or is advected to the oxygen gradient and precipitates as MnO_2. Since the sediments of the Puget Sound Ambient Monitoring Program station were low in Mn compared to the suspended sediment above them and since the overlaying water was high in dissolved Mn (Fig. 5), the particulate Mn formed in the water column in the vicinity of the Great Bend must settle to the sediments and again be solubilized within the sediment column.

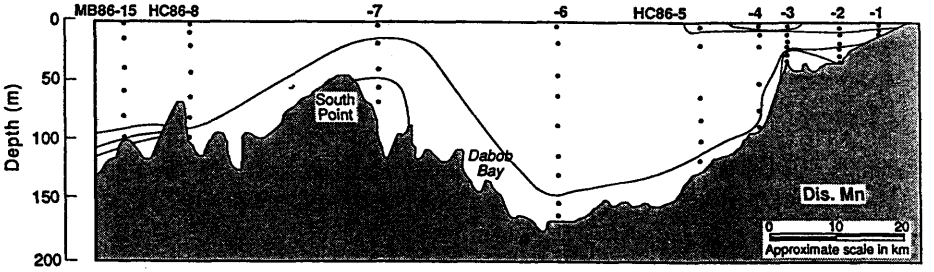

Figure 5.
DISTRIBUTION OF DISSOLVED MN IN HOOD CANAL (NM).

CONCLUSION

Fe concentrations of suspended particulates in Hood Canal were controlled by their aluminosilicate content and resuspension of Fe-rich sediments. Enrichments of Fe in Hood Canal sediments found by the Puget Sound Ambient Monitoring Program were not a result of increased Fe sources but were due to redistribution within the sediment column as a result of diagenic processes. In contrast to Fe, water column chemical processes redistribute Mn in Hood Canal. Particulate Mn is solubilized to the dissolved form in the water and sediment columns of Lynch Cove. The dissolved Mn is then transported to the oxygen gradient near the Great Bend where it precipitates and settles to the sediments only to be solubilized again within the sediment column.

ACKNOWLEDGEMENTS

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DIRECT TURBULENCE MEASUREMENTS IN PUGET SOUND [1]

Harvey E. Seim and Michael C. Gregg [2]

INTRODUCTION

Puget Sound consists of deep (150-300 m) basins interconnected by inlets which are generally shallower and narrower than the basins. Admiralty Inlet is a 30-km-long channel that connects the Sound to the Strait of Juan de Fuca (Figure 1). From north to south, Admiralty Inlet consists of a shallow (66 m) seaward sill which extends some 8 km landward from the entrance into the Sound, an intermediate reach which includes a deep hole (>150 m) just landward of the seaward sill and the branch to Hood Canal, and a deeper (100 m) but topographically rougher landward sill. The main basin of Puget Sound has an average depth of 200 m and joins both Admiralty Inlet and Saratoga Passage at its north end. The main basin in turn connects to basins farther south via a 9-km-long, 50-m-deep channel called The Narrows. Vashon Island splits the southern end of the main basin into two channels, East Passage and Colvos Passage; Colvos Passage is roughly half as deep (100 m) and half as wide as East Passage.

Currents are predominantly tidal, driven by 3-m mixed (both diurnal and semidiurnal) tides. Current amplitudes are greatest in the shallow inlets, exceeding 1 m/s in Admiralty Inlet and 2 m/s in The Narrows, whereas 0.2 m/s is typical in the main basin.

Originating in the Strait of Juan de Fuca, intrusions of salt water move south through Admiralty Inlet, which is longer than the average tidal excursion. Geyer and Cannon (1982) found that the intrusions penetrated to the main basin every fortnight, close to times of neap tide. They inferred that vertical mixing usually destroys intrusions before they reach the main basin, and that mixing is weakest when the tides are minimal. About 60% of the fresh water entering Puget Sound comes through Saratoga Passage at the seaward end of the main basin, an unusual situation for an estuary. Only 10% of the fresh water enters south of The Narrows, and the remaining 30% empties directly into the main basin.

This distribution of source waters and the variability in currents produce large variability in the stratification. The main basin is often capped by a fresh water lens, and the stratification decreases exponentially with depth. The Narrows

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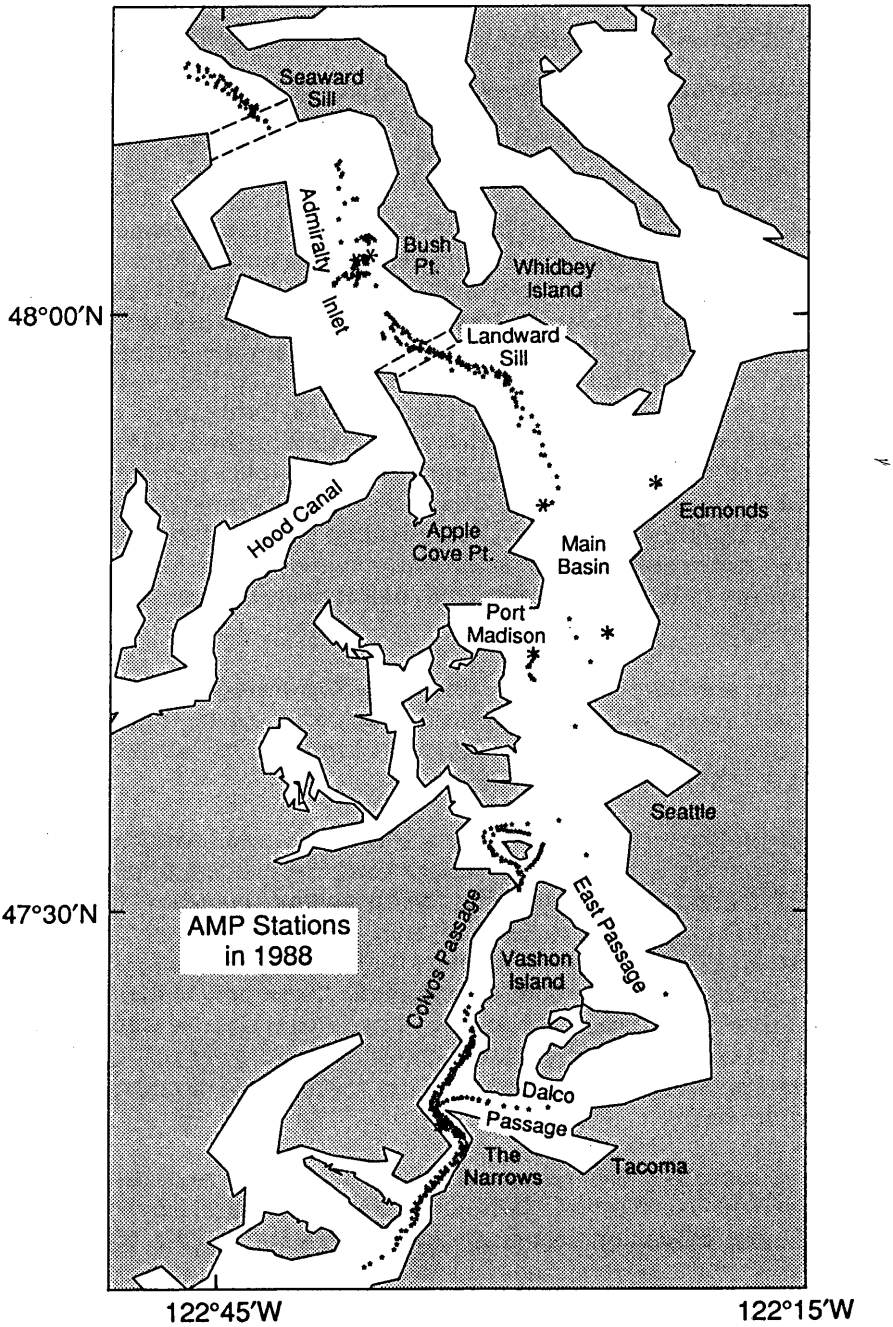

Figure 1.
***MAP OF PUGET SOUND** showing locations of AMP drops (small *) and time series measurements (large *).*

is often so well mixed that there is no stratification, whereas Admiralty Inlet at times resembles highly stratified estuaries. Such dramatically different physical conditions suggest a broad range of internal dynamics is active in Puget Sound, which makes it a difficult system to model. In particular, the variations in stratification imply that both boundary (or external) and free-shear (or internal) mixing occur at different times and places.

Previous observations give a crude description of the mean circulation, but little is known about the underlying dynamics. In the main basin, the density and oxygen at the bottom respond rapidly (in about one month) to increases in fresh-water input. Ebbesmeyer and Barnes (1980) speculate that this results from strong downwelling of surface water at the landward sill of Admiralty Inlet, with compensating upwelling at The Narrows. Geyer and Cannon (1982) suggest this downwelling may be assisted by a hydraulic jump over the landward sill.

Observations indicate the existence of a mean circulation around Vashon Island of $\approx 20{,}000\ m^3/s$ (Larsen et al., 1977; Bretschneider et al., 1985). Intense turbulence in The Narrows mixes water from the main basin with that from the southern basins and may produce enough net vertical exchange to drive the internal circulation in the main basin (Ebbesmeyer and Barnes, 1980).

In the following, we present a descriptive overview of our initial measurements of turbulence; details of how and where the measurements were made are given first, followed by results from Admiralty Inlet, the main basin, and The Narrows. Finally, we summarize the results and include a preliminary interpretation in terms of physical processes.

METHODS

During March through June of 1988, Washington State Sea Grant funded us for a pilot study of turbulence levels in Puget Sound. We used three instrument systems: the Advanced Microstructure Profiler (AMP), an RD Instruments acoustic Doppler current profiler (ADCP), and a BioSonics echosounder (Figure 2). Together, they provide simultaneous profiles of density, dissipation rate, current, and backscattering strength.

A loosely tethered free-fall profiler, the AMP measures conductivity and temperature as well as centimeter-scale shear and temperature gradients. The gradients are converted to dissipation rates of kinetic energy, ε, and of temperature variance, χ, respectively. These in turn are used in simple models (Osborn and Cox, 1972; Osborn, 1980) to estimate the vertical eddy diffusivity, K_d of heat and of density, e.g., $K_d < 0.2\varepsilon/N^2$, where N is the buoyancy frequency. For reference, ε is often about 10^{-9} W/kg in the oceanic thermocline, which for $N \approx 5 \times 10^{-3}\ s^{-1}$ gives $K_d \leq 10^{-5}\ m^2/s$.

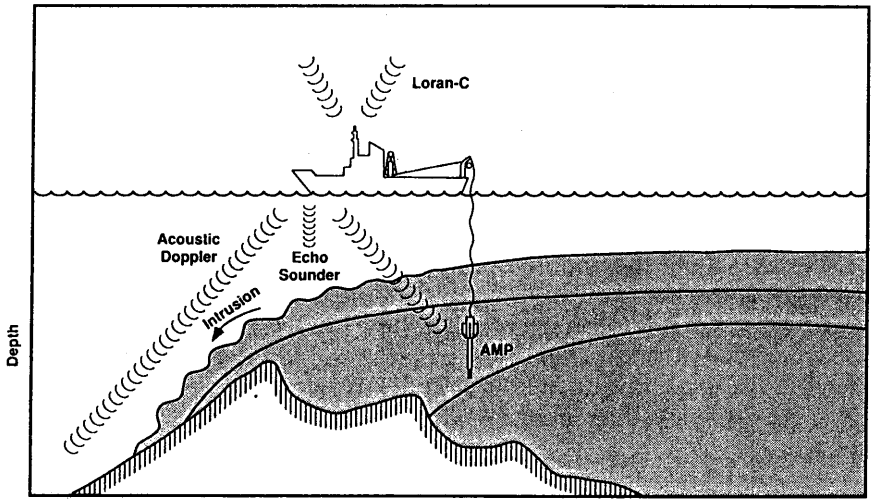

Figure 2.
SKETCH OF DATA-COLLECTION SYSTEM. *While AMP is deployed aft of the vessel, the ADCP and echosounder sample acoustically and the ship's position is monitored with Loran-C.*

The ADCP measures currents by their acoustic Doppler shift. We averaged acoustic returns over 2 minutes with a vertical resolution of 4 m. In most cases, the profiles are valid in the upper 85% of the water column. Obtaining absolute speed from bottom tracking often proved difficult, owing to the rugged topography.

The BioSonics echosounder measures backscatter intensity in a narrow beam beneath the ship every second with a vertical resolution of 1 m, providing an acoustic image of the water column. The acoustic return is proportional to the concentration of suspended material, mostly phytoplankton and zooplankton. As functions of time, the images are invaluable for interpreting AMP and ADCP profiles, which give an aliased portrait of rapidly evolving features.

We navigated using Loran-C with circular lines-of-position to obtain positions accurate to within about 100 m (Dunlap, 1989). Using these positions, we plotted bottom depth from a 15-second gridded bathymetric database, derived primarily from archived soundings at the National Ocean Survey (NOS). Tides at our positions were calculated with a linked channel model of the tides in Puget Sound (Lavelle et al., 1988).

Data were collected at anchor and under way during six separate 4-7 day cruises; we have organized the data into 52 bursts, each burst consisting of 3-50 consecutive AMP drops. In all, we made over 1100 AMP drops (Figure 1).

Contours of each burst reveal the evolution, in time or space, of structures in the water. In considering the results presented in the following section, it should be kept in mind that these data represent instantaneous conditions and therefore depend strongly on the tidal stage.

PRELIMINARY RESULTS

Admiralty Inlet

For the measurements in Admiralty Inlet, we concentrated on the seaward and landward sills and off Bush Point, finding very different dynamics at each site. At the seaward sill, we found tidal currents advecting strong horizontal density gradients back and forth, similar to a partially mixed estuary, and ε profiles suggesting that a bottom boundary layer dominates mixing. Off Bush Point, we discovered overturning billows and maximum ε at mid-depth, analogous to clear air turbulence. Anchored time series at the same site documented the arrival late on a flood tide of salinity intrusions, suggestive of an internal bore. The landward sill was very effective in producing internal waves, which appear to be unstable and break when exposed to average tidal currents, producing yet another mixing process.

Figure 3 is a contour plot of salinity from the southern end of the seaward sill south into the main basin, collected during an ebb tide. Several aspects of the salinity field are characteristic of other observations in Admiralty Inlet: a shallow lens of fresh water at the southern end; a vertical change in density approximately equal to the horizontal change in density across the inlet; and large vertical excursions of the isohalines (and isopycnals). The isohalines closest to the bottom (not shown) tended to hug the topography, but mid-depth displacements are not obviously related to the topography. Owing to the ebb tide, the saltiest water is present only at the seaward sill in this section.

Tidal advection of the horizontal density gradient was apparent from the average salinity increase of 1.5 psu we observed over a 6-hour span during a 4-m flood tide. We present two of the drops from the seaward sill in Figure 4. The most obvious features in the salinity profiles are large and small inversions, which result from turbulent overturns in the flow. Values of ε range from 10^{-7} to 10^{-4} W/kg and are an order of magnitude higher in the lower 20 m of the water column than elsewhere. Temporally, the burst-averaged ε varied by a decade, from 3×10^{-6} W/kg near low and high water to 3×10^{-5} W/kg during a few hours surrounding maximum flood currents.

Conditions during 2-m tides off Bush Point differ from those at the seaward sill. Stratification is stronger and dissipation is more patchy, with the highest ε values usually occurring at mid-depth. Overlaying an acoustic image with the ε profiles reveals overturning billows at 0.45 MPa, which are consistent

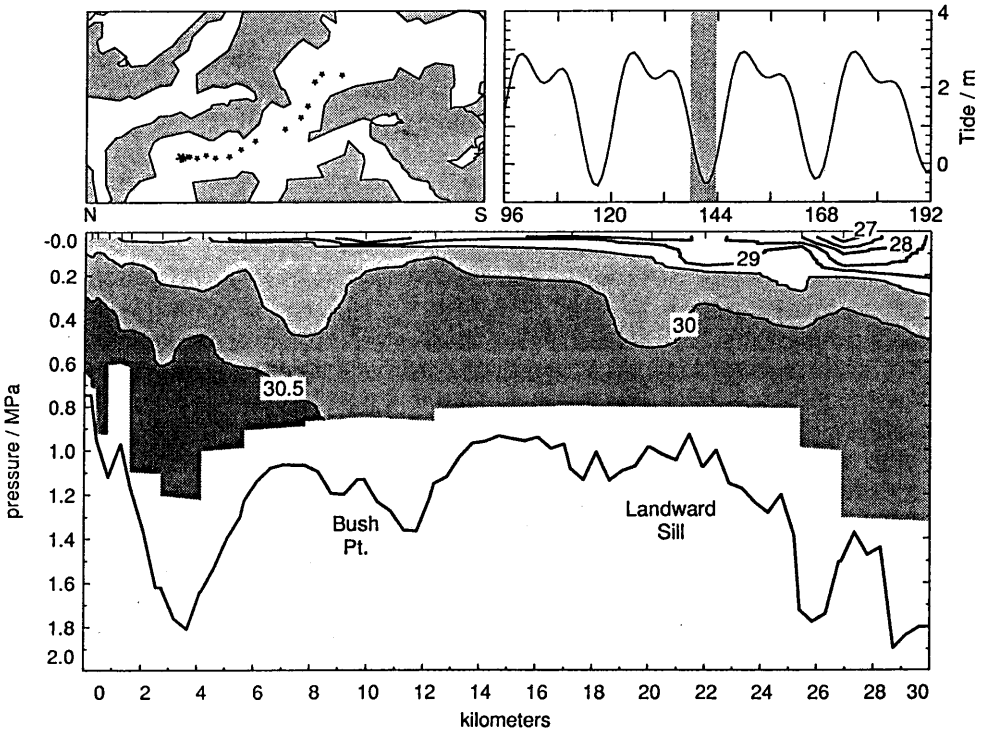

Figure 3.
THE BOTTOM PANEL IS A VERTICAL SECTION SHOWING SALINITY CONTOURS (IN PRACTICAL SALINITY UNITS) ALONG ADMIRALTY INLET DURING AN EBB TIDE. *Note that the vertical axis is pressure in megapascals; 1 MPa is approximately equal to 100 m. Drop locations are indicated by ticks along the top, and the thick black line marks the bottom depth, as determined from the NOS database. The upper-left panel gives the locations of the drops in plan view; the large asterisk marks the first drop. The upper-right panel shows the tides during the 5 days surrounding the sampling period, with the measurement interval shaded; the bottom axis is hours since the beginning of the month.*

with a Kelvin-Helmholtz instability (Figure 5). Dissipation rates in the billows are 2 decades higher than background levels, and suggest the instability may be producing the elevated ε values observed at mid-depth in this area. The billows generated eddy diffusivities of $K_d \leq 10^{-2}$ m²/s and overturns of 10 m which decayed slowly over half an hour.

We also made two anchored time series at Bush Point during 3.5-m flood tides. In both cases, an intrusion with 0.8 psu higher salinity arrived shortly after maximum flood currents, producing the peak ε values for the time series. In contrast to the outer sill, the background, depth-averaged ε (i.e., excluding ε values associated with the intrusion) was highest around low and high water

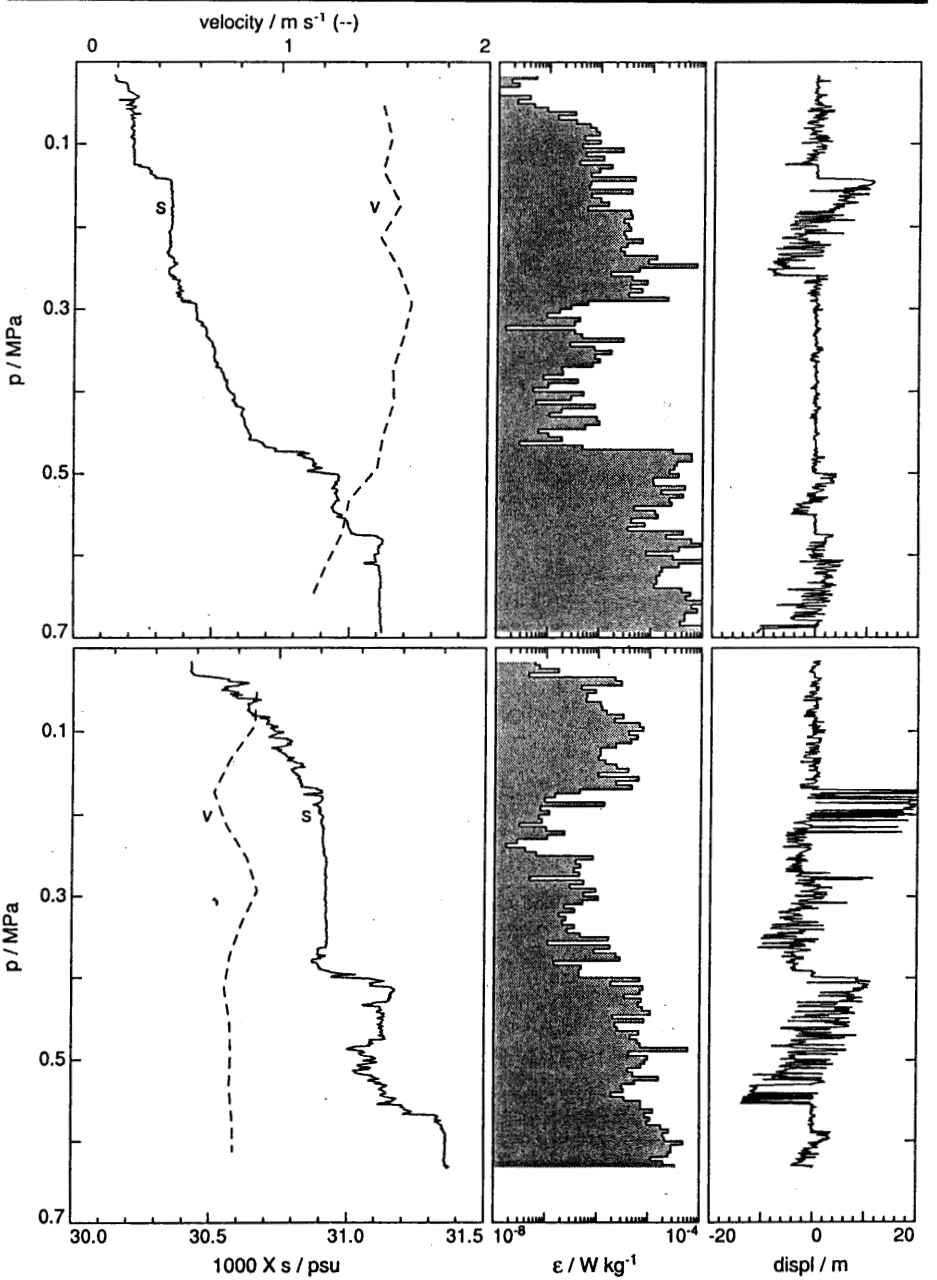

Figure 4.
DROPS 6554 (TOP) AND 6570 (BOTTOM), *taken 2 hours apart during a 4-m flood tide at the seaward sill. Left panels are profiles of salinity (solid line) and velocity (dashed line); center panels are ε profiles, and right panels are the displacement profiles, showing the thickness of vertical overturns. Note differences in salinity between drops and the enhanced ε near the bottom.*

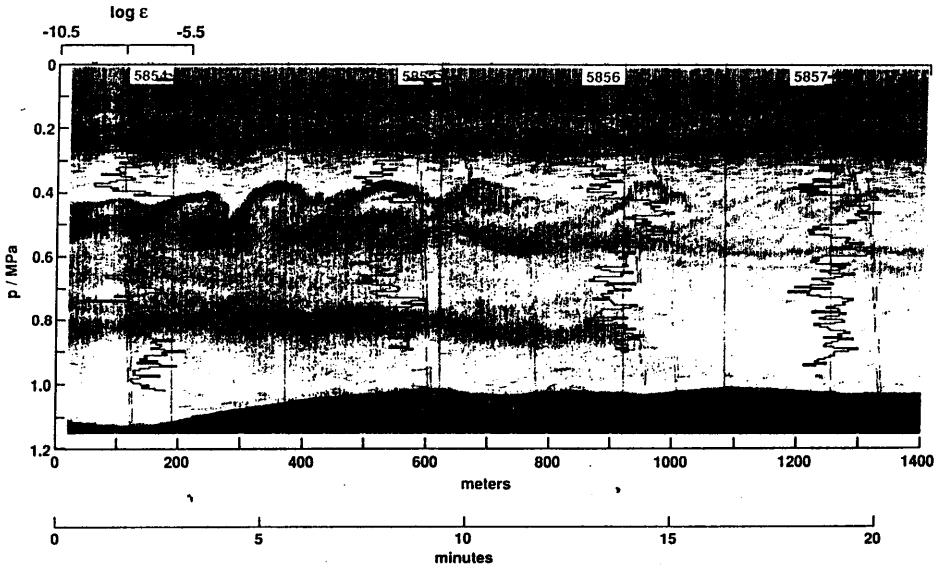

Figure 5.
***ACOUSTIC BACKSCATTER IMAGE** collected off Bush Point overlaid with profiles of log ε measured concurrently. The wavy feature at mid-depth is thought to be a Kelvin-Helmholtz instability.*

and less during mid-flood. At its head, the intrusion covered half the water depth and thinned rapidly with time.

Most remarkable at the landward sill were the large wave-like displacements of the isopycnals downstream of the sill, even when current speeds were low (Figure 6). Note the strong surface ε associated with a rapid deceleration of the flow at 6.25 km, and the marked increase in the depth of the fresh-water lens. We suspect these signify an internal hydraulic jump. The surface layer is hydraulically supercritical, as shown by the densimetric Froude numbers; $F_d \equiv U/\sqrt{g'h}$, where U is flow speed, $g' \equiv (\Delta\rho/\rho)g$ is the reduced gravity, and h is the layer depth. Upstream of the jump, F_d is 1.5 and 0.5 for the upper and lower layers, respectively ($F_d < 1$ indicates subcritical flow). Mixing associated with the jump would be an effective mechanism for "downwelling" water at the landward sill.

At higher flow speeds, the isopycnals lose most of their wavy character, shifting to almost step like changes tens of meters thick. At the same time, turbulence increases dramatically, peaking at $\varepsilon > 10^{-4}$ W/kg. The densest water passing over the sill is often very turbulent, and forms a nearly well-mixed layer as it moves into the northern main basin, with associated overturning scales exceeding 20 m.

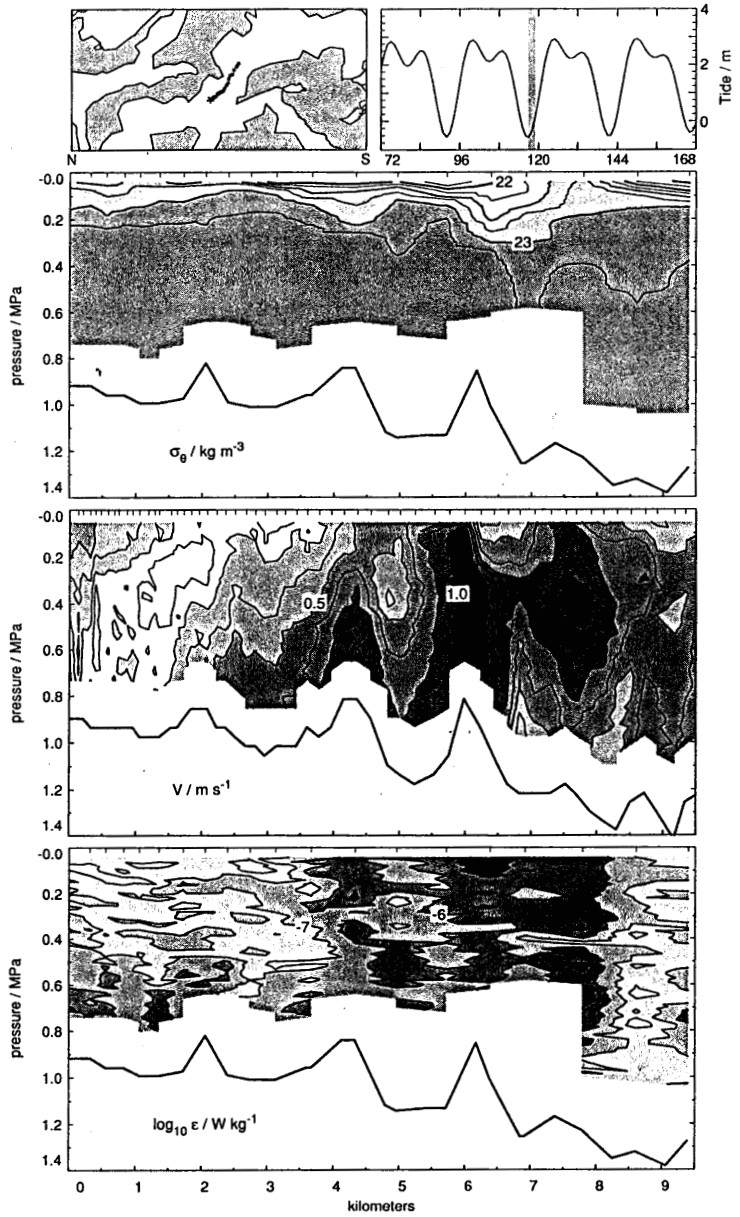

Figure 6.
CONTOUR PLOTS OF DENSITY (σ_θ), CURRENT VELOCITY (V), AND LOG ε *observed in a section across the landward sill of Admiralty Inlet. The top two panels are described in Figure 3. At 6.25 km, note the increase in the depth of the fresh-water lens, the velocity change, and the high ε in the upper water column, thought to be signatures of an internal hydraulic jump. Froude numbers are 1.5 and 0.5 for the upper and lower layers, respectively.*

Main Basin

Our observations in the main basin were limited to four short (<12-hour) time series collected at various sites north of Seattle. Most notable was the spatial variability and range of phenomena observed. All but one of the time series were collected on tides less than 2 m; the high ε for these measurements was due to mid-depth intrusions and turbulent patches similar to those observed in the oceanic thermocline. Internal waves with a period of 12 hours and an amplitude of 20 m, reminiscent of a diurnal internal tide, were observed off Edmonds. The time series collected during 4-m tides was much more energetic, suggesting conditions may be quite different for larger tides.

Off Port Madison, conditions were relatively quiet. A fresh-water lens initially capped the water column, weakening in strength with the ebbing tide. Isopycnals were relatively flat, and ε exceeded 10^{-7} W/kg only in thin patches above 0.7 MPa, lasting at most an hour. Below 1 MPa, ε was low, averaging only 6×10^{-9} W/kg and yielding $K_d \approx 4 \times 10^{-4}$ m^2/s.

Off Shilshole Bay, just east of Port Madison, conditions were quite different. The biggest change was the presence through ebb tide of a 0.7-MPa-thick intrusion, centered at 1.15 MPa. The intrusion dominated the dissipation rate profiles, as illustrated in Figure 7. Sustained dissipation rates of 5×10^{-7} W/kg were associated with the intrusion, with peak values of 10^{-5} W/kg; $K_d \geq 10^{-3}$ m^2/s resulted. Presumably because of increased internal wave activity, isopycnal movement throughout the water column was greater at Shilshole Bay than at Port Madison. Typically, isopycnals rose and fell a few meters over fractions of an hour.

The day after the measurements off Shilshole Bay, we found a cold-water intrusion while anchored just north of Edmonds. Also centered near 1.15 MPa, it had no ε signature. The dissipation rate was low, averaging 10^{-8} W/kg below 0.2 MPa and yielding $K_d \leq 10^{-4}$ m^2/s. Most interesting at this site was the change in stratification at mid-depth due to low-frequency heaving of the isopycnals. This suggests the presence of a low-mode internal wave, not found farther south in the basin.

A week later off Apple Cove Point during a 3.75-m tide, the fresh-water surface lens was absent, resulting in weaker stratification above 0.5 MPa, and isopycnal displacements were much larger. Dissipation rates on ebb tide were large only near the bottom, but the region of high ε grew after low water, reaching 10^{-7} W/kg in the lower half of the water column an hour and a half after the flood tide began. Roughly an hour afterward, isopycnals rapidly oscillated 20-60 m, and ε increased by 1-3 decades over the entire water column, presumably the result of a front passing through. Diffusivities at this site generally exceeded 10^{-3} m^2/s.

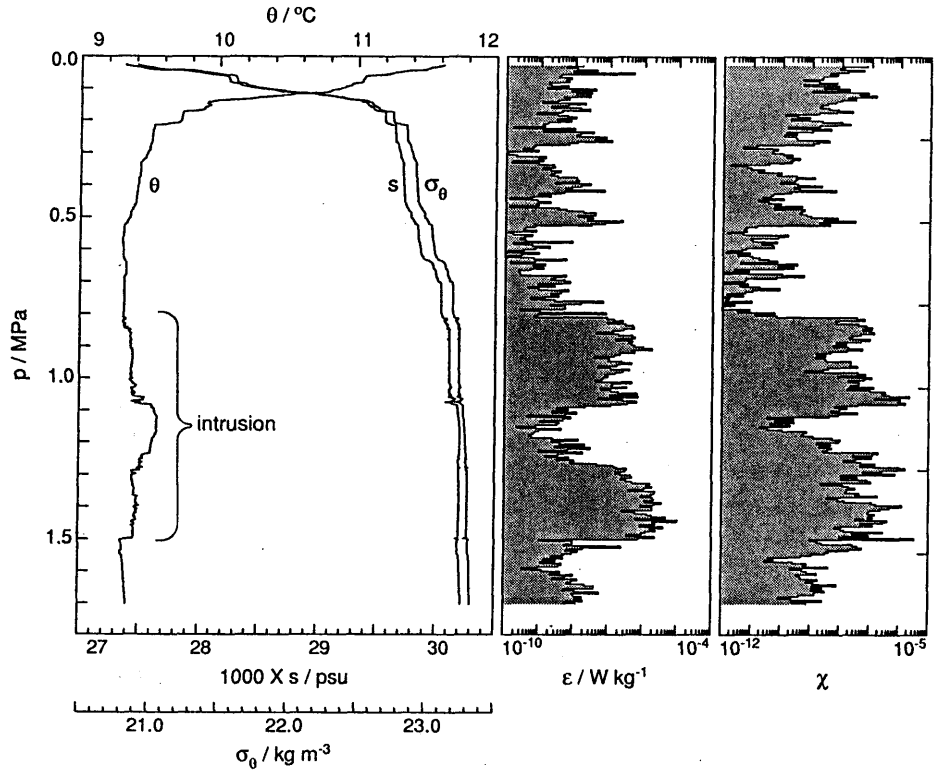

Figure 7.
PROFILES OF TEMPERATURE (Θ), SALINITY (S), DENSITY (σ_θ), ε, AND χ FOR AMP DROP 6395, *taken off Shilshole Bay. A 0.7-MPa-thick intrusion centered at 1.15 MPa dominates dissipation rates in the water column.*

The Narrows

Stratification in The Narrows is much weaker than in Admiralty Inlet or the main basin, but truly well-mixed conditions are episodic and occur only south of the bend at Point Evans on flood and north of it on ebb. The Narrows typically was weakly stratified when the tide turned. Figure 8 shows a transition to well-mixed conditions. The water column is completely overturned, and, surprisingly, the densest water is on top and is much more homogeneous than the underlying water. The maximum dissipation rate, $\varepsilon \approx 10^{-3}$ W/kg, was commonly observed during overturning.

Large vertical excursions of isopycnals entering and exiting The Narrows indicate that mixing here involves all the water masses present in the main basin and the southern basins. A section from Dalco Passage into The Narrows (Figure 9) shows dense water ($\sigma_\theta > 23$) rising more than 0.5 MPa on a minor

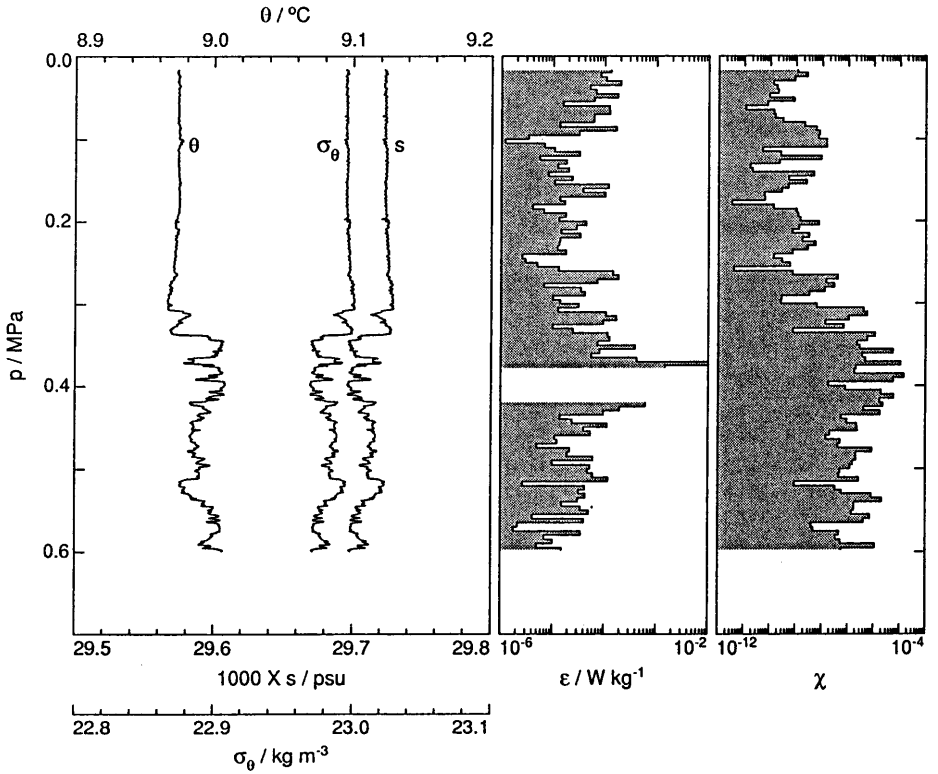

Figure 8.
PROFILES FOR AMP DROP 6109, *taken during a time series in The Narrows as the water column transitioned to well-mixed conditions. Variables are defined in Figure 7. The missing ε data are due to a taut cable, and the regular oscillations of the hydrographic fields above 0.3 MPa are caused by noise on the thermistor circuit. Note that the densest water, in the upper half of the water column, is nearly homogeneous, whereas the underlying water is not.*

flood tide. Similar "upwelling" events were observed on ebb tide at the south end of The Narrows when dense water entered from the southern basins. Isopycnals plunge on ebb tide as water exits The Narrows into Colvos Passage. Dissipation rates commonly were an order of magnitude higher in The Narrows than in any of the passages that feed into it.

SUMMARY

These data are the first turbulence measurements in Puget Sound, as well as some of the highest spatial and temporal resolution hydrographic measure-

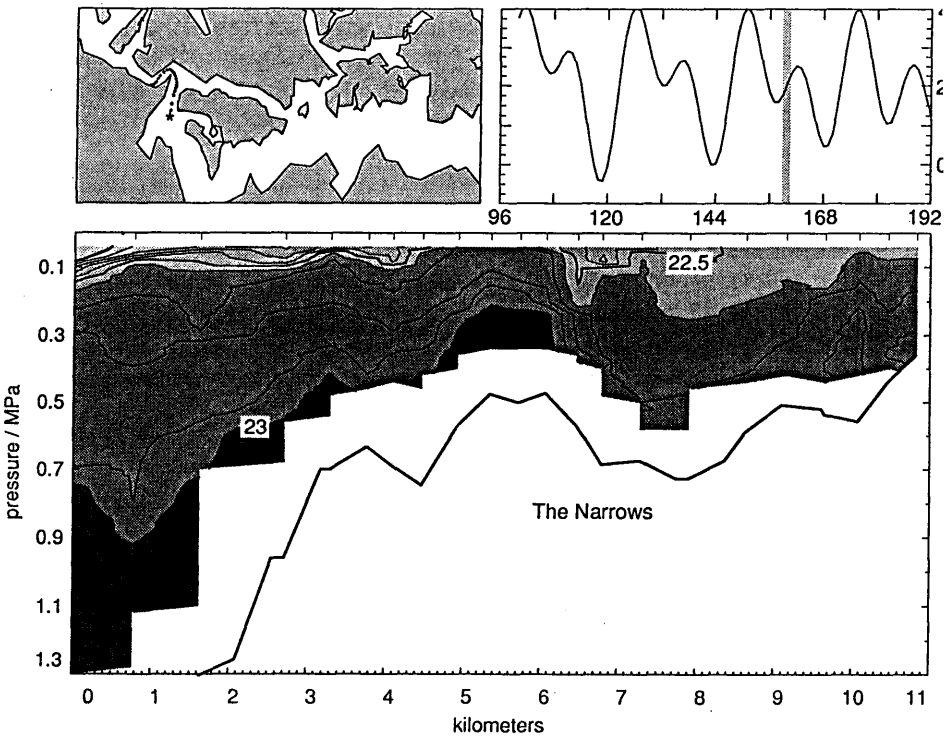

Figure 9.
CONTOUR PLOT OF DENSITY *beginning in Dalco Passage, west of Tacoma, and passing into The Narrows on a minor flood tide showing a 50-m rise in the 23* σ_θ *density surface. Upper panels are described in Figure 3.*

ments. The general character of the observations is consistent with previous measurements, but they reveal a greater level of complexity:

- In most of the measurements, which were collected from March to June 1988, a fresh-water lens (1-3 psu) capped the water column in the northern main basin and southern Admiralty Inlet, yielding an average salinity stratification of £4 psu over the inner sill in contrast to the 1 psu found by Geyer and Cannon (1982). This is significant because it makes the net horizontal and vertical density differences across Admiralty Inlet roughly equal, indicating the estuary may support a barotropically driven internal tide (Jay and Smith, 1990). These may be the dynamics of the bore-like intrusion observed off Bush Point.
- Mixing over the seaward sill was dominated by a turbulent boundary layer, as suggested by enhanced ε values near the bottom whose amplitude varied in phase with the current speed. Background ε at Bush Point was highest

near slack water and greatest at mid-depth, suggesting free-shear instabilities drive vertical mixing in this part of the inlet. The landward sill was very efficient at generating internal waves (presumably lee waves), which appear to be critical for typical tidal currents and lead to internal hydraulic jumps as suggested by Geyer and Cannon (1982).

- The mid-depth intrusion observed off Shilshole Bay which produced vigorous mixing over a 70-m segment of the water column for at least 6 hours, clearly demonstrates that the main basin is not always quiescent. The high turbulence levels measured off Apple Cove Point suggest either that Admiralty Inlet's influence extends well into the main basin or that ε is in some sense strongly dependent on tidal range.
- The 12-hour period of the low-mode isopyncal displacements just north of Edmonds suggests the presence of a diurnal internal tide, which would be evanescent and, since it was not observed farther south, is either highly directional or intermittent.
- The strong upwelling of lower-layer water into The Narrows from both Dalco Passage and the southern basin provides an effective means of accomplishing vertical mixing, since water passing through The Narrows is often well mixed.
- Consistent with observations by Ebbesmeyer and Barnes (1980), well-mixed conditions in The Narrows were observed only downstream of the bend at Point Evans. This restriction either gives a measure of the length required for the turbulent boundary layer to grow to the depth of the water column or implicates lateral circulation, due to the bend, as the force that generates well-mixed conditions.

In addition to revealing a wealth of mixing processes, these preliminary observations taught us that we cannot fully understand the generation and evolution of turbulence without simultaneously mapping the nearby water masses, fronts, and internal bores. To this end, Sea Grant is funding us to develop a towed mapping system for further work in the Sound.

ACKNOWLEDGMENTS

We gratefully acknowledge support for collection of these data by the Washington State Sea Grant Program and its director, Louie Echols. The analysis of the data and Mr. Seim's salary were funded by The Mixing to Mesoscale University Research Initiative of the Office of Naval Research. We also thank Tom Sanford and John Dunlap for the loan of the Loran equipment, Jamie Morison for the use of the ADCP, Hal Mofjeld of PMEL for directing our sampling, and Bill Lavelle for the bathymetry data and the tidal model. Lastly, we recognize the dedicated work of Dale Hirt, Jack Miller, Bob Miyamoto, Steve Bayer, and Donna Sorensen in collecting the data and maintaining the instrumentation.

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ACOUSTIC MONITORING AND TRACKING OF WASTEWATER PLUMES

Atle Lohrmann[1] *and Curtis C. Ebbesmeyer*[2]

INTRODUCTION

Traditionally, plumes of suspended material have been detected and quantified with one or several single-point measurement devices, ranging from the use of temperature and salinity as passive tracers, to more direct measurements of optical transmissivity, or of dye released from outfalls.

The problem with tracking and quantifying wastewater plumes, however, is the non-uniformity in the distribution of suspended material. Rather than being distributed homogeneously, the wastewater is trapped in small and large parcels. This non-uniformity requires dense horizontal and vertical sampling before reliable statistical estimates of particle distribution can be obtained. Normally, this is not done because the single-point measurement devices used are limited to measuring over a small region at any given time. A sufficiently dense sampling grid can only be provided with a great effort in time and resources. As a consequence, it is almost impossible to obtain adequate statistics for suspended material. Important parameters, such as dilution rates or toxicity levels, are difficult to estimate. Measurement of acoustic backscatter is an alternative that may solve some of the problems inherent to these single-point measurements.

Acoustic backscatter devices transmit an acoustic pulse and continually detect the echo. In contrast to single-point measurement devices, this method provides instantaneous measurements throughout the water column. Further, because backscatter is measured simultaneously over the full vertical range, the time required to survey an area is significantly reduced. The sampling rate is limited only by the speed of sound (typically 1500 m/s), implying that the upper 200 meters of the water column can be surveyed with 1 meter vertical and horizontal resolution from a boat that is rapidly traversing a cross section (e.g., 6 knots).

The use of echo sounders to detect the bottom and to detect fish in the water column are well-established methods; there is little new about the use of acoustics to detect suspended particles. Finding schools of fish has parallels to the problem at hand, the difference being size of the "particles". As a conse-

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quence, scientists have pursued this method of detection. Examples includ Holliday and Pieper (1980) and Flagg and Smith (1989) using acoustic back scatter to quantify zooplankton concentration; Hanes et al. (1988) and Libick et al. (1989) using high frequency (>2MHz) acoustics to detect resuspende bottom sediments, and Proni (1975), who has used acoustics as a qualitativ tool to track waste water plumes for a number of years.

WATER STRUCTURE IN PUGET SOUND

Two mechanisms have been observed in which the water and the particle from a typical sewage outfall become contained in irregularly separate lenses. First, there is a tendency for the sewage to be separated into smal pockets within the ambient water as part of the convection and diffusio taking place as the effluent rises from the outfall and is advected downstream Secondly, the effluent may be trapped inside lenses of ambient water that ar separated according to local dynamic conditions. The latter mechanism seem to be especially important in the Puget Sound area.

Until the 1960s, observations of water quality in Puget Sound were made a discrete depths using water bottles tripped at selected depths. At that time, i became possible to sample the vertical structure rapidly with electroni temperature and salinity sensors lowered through the water column. Th introduction of these devices, known as STD's (salinity-temperature-depth and CTD's (conductivity-temperature-depth) allowed the vertical samplin interval to be decreased from 5-25 meters to 1 meter or less. The horizonta sampling interval is limited by the time it takes to lower the instrument an need to cover a large area.

At several locations in Puget Sound, the water structure has been studied i detail using temperature and salinity data sampled at one meter vertica resolution. With this increased resolution the water structure has often bee found to consist of discrete lenses of water. Detailed studies have been carried out in Dabob Bay and throughout the Main Basin of Puget Sound extendin from Admiralty Inlet to The Narrows.

Dabob Bay

Collection and treatment of the observations may be briefly summarized as follows. STD casts were obtained at 1 kilometer intervals on the longitudinal axis of Dabob Bay. Temperature averages were computed within 2 mete vertical intervals, and then smoothed horizontally every 200 m using cubic splines. Figure 1 illustrates two water lenses observed in the data se (Ebbesmeyer et al., 1975).

The circulation in Dabob Bay is typically estuarine with inflow underlying outflow. The surface has relatively low salinity and overlies a sharp salinity-controlled pycnocline. In the variable depth inflow zone, between approximately 60 m and the sill depth at 120 m, salinity gradients are relatively small. The effect of temperature on density is such that relatively high-temperature, high-salinity intruding waters interleave as layers or become occluded as lenses in ambient water of comparable density. The mean features of the salinity and temperature structure can be used to follow the seasonal changes. Although both these variables, and density, must be used in a definitive analysis of water structure and circulation, the major features of the flushing of basin water are shown by successive temperature patterns. Over brief periods, the changes in the structure and properties of the larger lenses can be used to give a quantitative measure of the movement of water within the estuary.

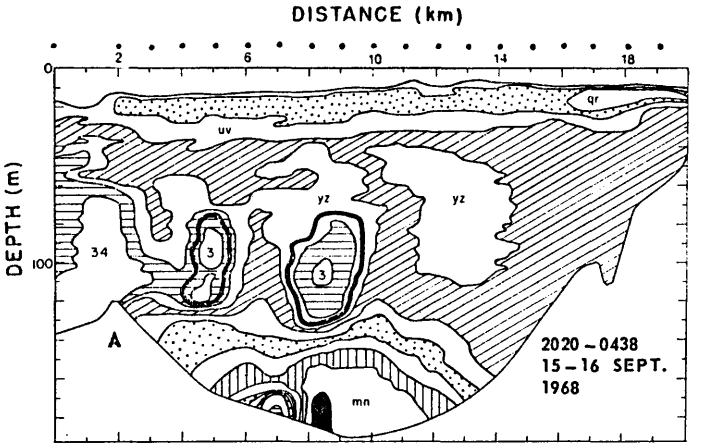

Figure 1.
***TEMPERATURE IN DABOB BAY** observed during 2020-0438 on 15-16 September 1968 contoured at 0.2 degrees C (from Ebbesmeyer et al., 1975). Two water parcels are outlined by heavier weight contours.*

Main Basin

For ten years (1974-1984), observations were conducted with CTD's and dye sensors in the Main Basin of Puget Sound. To trace the sewage, Rhodamine B dye was injected continuously into the West Point effluent, and its concentration, along with temperature and salinity, was measured using a sensor package towed horizontally and cycled vertically. This yielded quasi-vertical profiles of dye and the associated density field.

Comparison of the numerous dye and density profiles collected by Bendiner (1976) showed the vertical distribution of effluent at a given location to be correlated with the density profile at that location. Almost without exception, the dye was constrained by sharp density gradients and lay within vertical intervals of weakly stratified water. By contouring the density field and dye concentration from several profiles taken along a transect (Fig. 2), it became evident that the areas of concentrated dye were located within separate water lenses composing the density field.

CTD profiles taken along the Main Basin at monthly intervals during 1982-1984 confirmed that similar water lenses were present throughout the year (Ebbesmeyer et al., 1987). The situation shown in Figure 2 is considered typical. The implication is that lenses are common at all water depths and throughout the year.

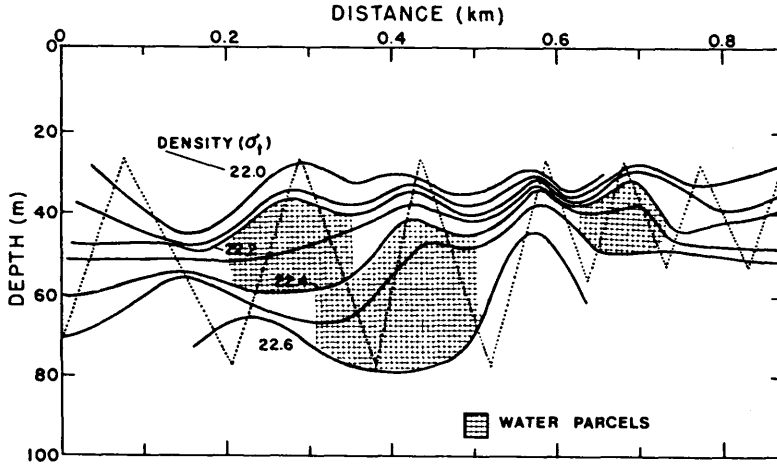

Figure 2.
VERTICAL SECTION OF DENSITY OFF WEST POINT. *Codes: Solid lines, density contours; dotted lines, trajectory of towed probe; and cross-hatched areas, water parcels (adapted from Bendiner, 1976)*

ADCP BACKSCATTER MEASUREMENTS

The acoustic Doppler current profiler (ADCP) was developed to measure the Doppler shift of an acoustic echo. The Doppler shift depends linearly on the velocity along the acoustic beam and the horizontally averaged mean velocity vector is obtained by combining the Doppler shift data along a minimum of three acoustic beams. As a byproduct of these measurements, intensity of the echo is estimated by the Automatic Gain Control (AGC) and stored. The AGC level can be used in combination with estimates of transducer efficiency,

beam angle, pulse length, etc., to calculate the absolute volume backscatter at a given depth.

For the purpose of detecting local anomalies in the acoustic backscatter, the echo only needs to be normalized with respect to range. This is done simply by adding the terms for acoustic absorption and geometrical spreading to the recorded AGC. Therefore, without any additional calibration, the ADCP is both a current profiler and a "volume backscatter anomaly" profiler. To find the absolute backscatter a relatively complicated calibration must be performed.

The relationship between particles of irregular shape and volume backscatter is, in general, not well known. In the limit when the particles are much smaller than the acoustic wave length, scattering is assumed to follow the equation first derived by Rayleigh (Urick, 1983):

$$\sigma = bk^4 \sum_{i=1}^{n} a_i^6,$$

where σ is the volume backscatter, a_i is the radius of the individual particles, k is the acoustic wave number, and b is an unknown constant.

The central feature of this equation is the strong dependence on particle size. To find the total volume of suspended particles based on a measure of σ, the size a_i must be known to avoid significant errors. In the Rayleigh regime (small particles), further effort is thus required before backscatter profilers can be used as particle concentration profilers. However, for a given distribution of particles of different sizes, the backscatter is proportional to the concentration of material. For a given plume, it is therefore reasonable to expect that the horizontal variation in the AGC is proportional to the variation in concentration. An increase in backscatter of 3 dB corresponds to a doubling of particle concentration.

EXAMPLES OF BACKSCATTER DATA

The first set of current velocity and range-normalized backscatter data was collected using a 150-kHz ADCP with 1 meter vertical resolution along the dominant current direction over a major sewage outfall in the Oslofjord, Norway. The sewage undergoes secondary treatment and oxygen is added before release. The water column is stratified, with a pycnocline situated about 15-20 m below the surface.

After discharge, the material rises from the outfall located 55 m below the surface to the pycnocline (Fig. 3). The material is concentrated in a layer

extending 5 m in the vertical as it is advected downstream. The plume can be observed acoustically 500m from the outfall. In the contour plot of acoustic backscatter, the plume seems to follow the dynamics of a typical smokestack. In contrast to visual observation of smokestacks, however, the material is concentrated in small packets inside the borders of the plume rather than being uniformly distributed. This agrees with the idea that the material separates into pockets during the initial convective stage.

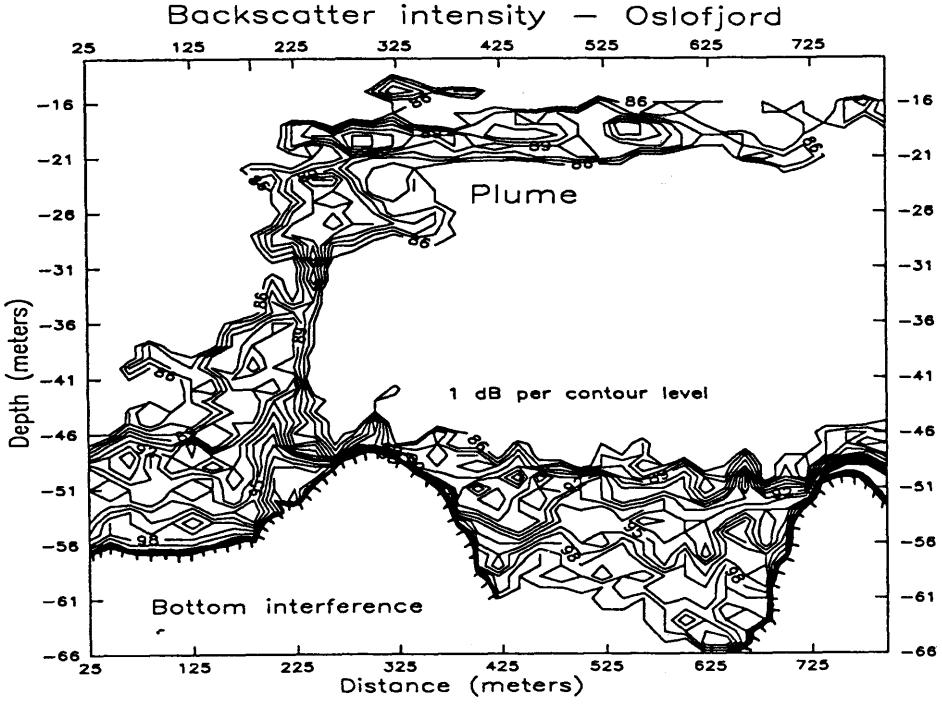

Figure 3.
ACOUSTIC BACKSCATTER NORMALIZED WITH RESPECT TO RANGE. *The data were collected in April 1990 with a 150 kHz ADCP mounted on R/V Trygve Braarud. The high backscatter levels close to the bottom have not yet been explained.*

The second set of data was collected from a survey vessel crossing a sewage pipe located off Newport Beach, Orange County, California. The total flow in the diffusers varies between 12 and 23 m^3/s (265 and 530 million gal/day), and the effluent material is released through a series of horizontal ports spaced 12 feet apart. The initial concentration of material was significantly lower than for the Oslofjord outfall.

During a survey in January, 1990, the range-normalized backscatter data (Fig. 4) showed a classic winter situation without pronounced stratification. As

expected, the effluent moved rapidly to the upper layer rather than being trapped in the pycnocline. The survey vessel crossed at an angle perpendicular to both the current velocity and the pipe. The data include only the rising effluent and the quasi-stationary cloud of material above the diffuser. The variation in concentration downstream remain unobserved for this location.

The data in Figure 4 also points to a potential pitfall of using acoustic backscatter to observe sewage plumes: the acoustic similarity of effluent material and other scatters such as fish and zooplankton. In Figure 4, there seems to be a 200 m wide cloud of rising material above the pipe. Closer inspection, including an analysis of the detailed velocity structure, showed this "rising cloud" to be dominated by a large school of fish.

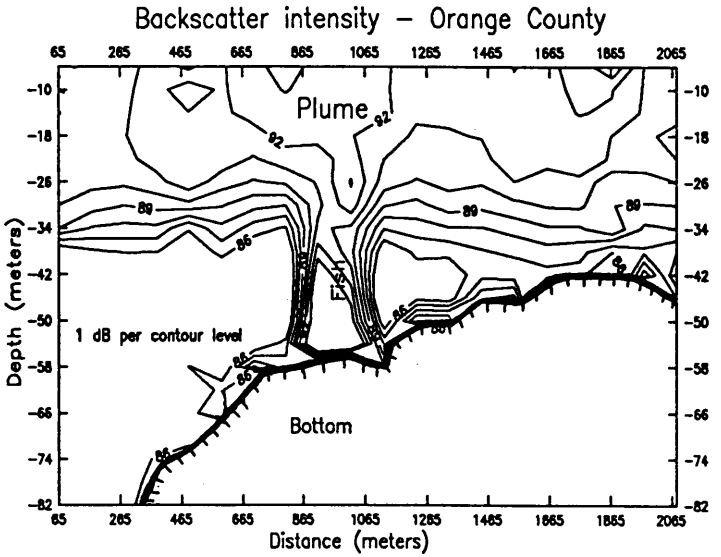

Figure 4.
ACOUSTIC BACKSCATTER DATA COLLECTED WITH A 600 KHZ ADCP IN JANUARY 1990. *The data were collected over a sewage outfall off Newport Beach, California. The horizontal distribution of backscatter is more uniform than in the Oslofjord.*

CONCLUSIONS

The dynamics of sewage plumes seem to take place on a series of different scales. The main scales are defined by the size of the plume itself and by the scale of the ambient turbulence. Close to the outfall (<500 m), the acoustic measurements from the Oslofjord and results by J.Proni (personal communication) show that the effluent may be separated into small pockets extending 1-5 m in the vertical and 5-50 m in the horizontal depending on the density

stratification. The separation takes place both during the buoyant convection stage immediately after discharge and as a product of later dynamic processes.

Further downstream, the fate of the effluent is determined by the dynamics of the ambient water. The measurements in Puget Sound shows the ambient water to be divided in horizontally elongated lenses with different hydrographical characteristics. These lenses survive for distances of tens of kilometers and they are common at all water depths and throughout the year. Once effluent is entrapped inside a lens, the rate of dilution is substantially reduced.

The implication of these measurements is that the distribution of material is intermittent, both near the outfall and in an area extending several kilometers downstream of the outfall. Dilution rates and toxicity levels can be calculated correctly only if the plume measurements are made at horizontal and vertical scales smaller than the size of the small and large parcels. In the few examples we have studied, 1 meter vertical and 10 meter horizontal intervals appear to be the appropriate sampling scales.

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HIDDEN SIGNALS IN THE WASHINGTON STATE CLIMATE RECORD

Wendell Tangborn[1], *Curtis Ebbesmeyer*[2] *and Edward LaChapelle*[3]

INTRODUCTION

Climate trend analyses based on daily, monthly and annual temperature means present only part of the global warming picture. Additional information is also available from daily maximum and minimum temperatures. Using these data to sort clear days from cloudy days at stations with reliable, long-term records reveals the existence of temperature trends contrary to those derived only from daily means. Such sorting also identifies a shift to greater climate variability during the latter half of the examined period of record, a shift not readily apparent in standard climate analysis.

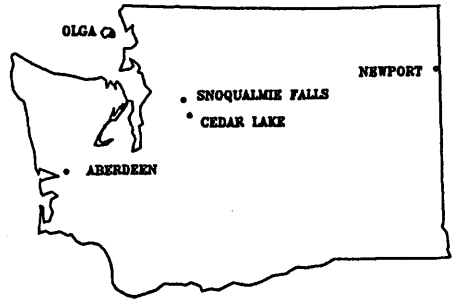

Figure 1.
WEATHER STATIONS USED IN THIS STUDY.

SETTING

To examine climate changes in the Puget Sound region, weather data were compiled from five long-term stations in the Pacific Northwest. Three of the stations were in the Puget Sound region and two others outside the Puget Sound but in the state of Washington (Figure 1). None of these stations appear to be affected by urbanization; however, as with most climatic stations, these

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have been subjected to site and observation time changes and the data need to be treated with caution. All five stations produced similar results in this study. The local climate at each of the stations varies considerably (Table 1).

Weather Station	Period	Elevation (feet)	Mean Annual Temperature (°F) Max	Min	Range	Precip (inches)
Aberdeen	1932-88	10	58.4	42.4	16.0	83.4
Olga	1892-88	80	56.9	42.3	14.6	29.0
Snoqualmie Falls	1899-88	440	60.1	40.8	19.3	58.5
Cedar Lake	1932-88	1560	55.4	39.5	15.9	101.8
Newport	1931-88	2135	58.1	32.0	26.1	27.1

Table 1.
SUMMARY OF WEATHER STATION CHARACTERISTICS

APPROACH

Analysis of global temperature records for the past 100 years using annual averages of mean temperatures does not show the increases that might be expected due to the greenhouse effect. The usual values cited are an increase of from 0.3 to 0.6° C (.5 to 1 degree F) since the turn of the century (Mitchell, 1989). Many climatologists claim this amount is insignificant compared with temperature measurement errors, while others state that although this increase may be real, there is no evidence it is linked to greenhouse effects. However, there is little doubt that atmospheric carbon dioxide has shown a nearly 20 percent increase since the turn of the century, with three-fourths of this increase occurring since 1960 (Figure 2; Siegenthaler and Oeschger, 1987). There are examples where the temperature has even decreased since the turn of the century (Figure 3).

A new approach is presented for analyzing long-term temperature data in the Pacific Northwest based on the separation of temperature into regimes determined by the diurnal temperature range (the difference between the daily maximum and minimum temperature). Maximum and minimum measurements have been made at thousands of weather stations throughout the world for over 100 years. The diurnal temperature range is strongly related to cloud cover and other atmospheric conditions (for example, haze and humidity); a low range signifies cloudy, moist conditions and a high range indicates clear skies and a dry atmosphere (Tangborn, 1980).

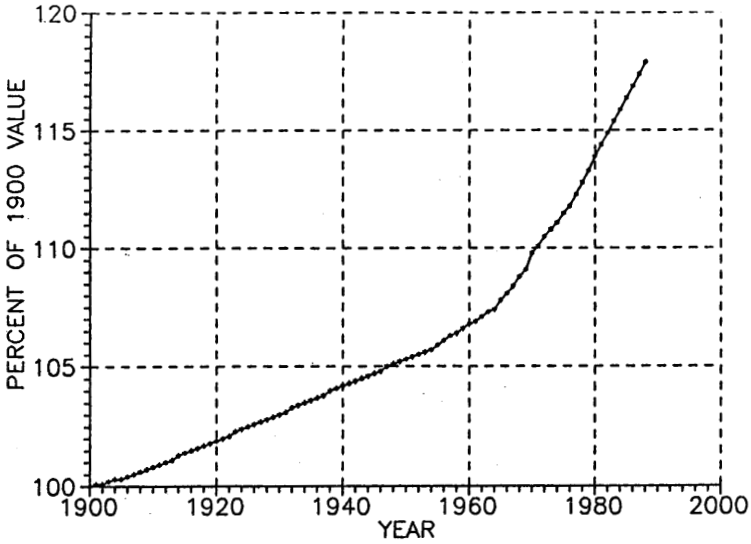

Figure 2.
ATMOSPHERIC CARBON DIOXIDE 1900-1986 *as determined by air bubbles in glacier ice and since 1957 by direct measurements. Shown as percent of the 1900 value of 296 ppm. Adapted from Bolin et al. (1989).*

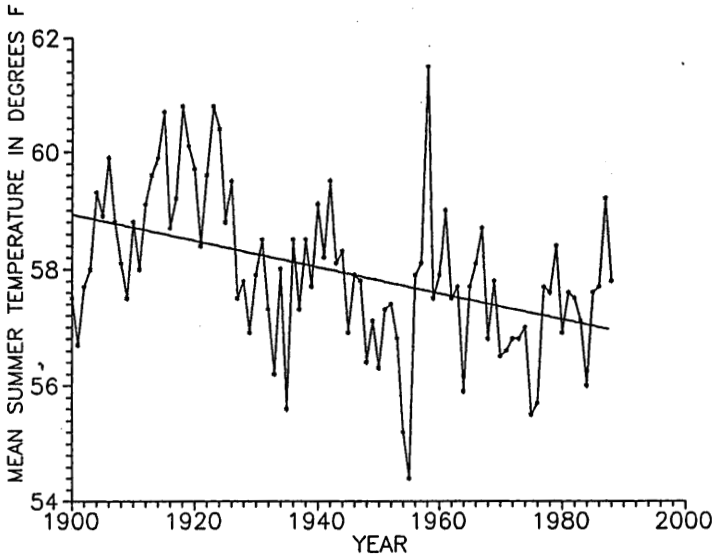

Figure 3.
MEAN APRIL-SEPTEMBER TEMPERATURE *at Snoqualmie Falls, Washington for the 1900-88 period.*

RESULTS

The distribution of the daily temperature range for Snoqualmie Falls reveals some interesting patterns (Figure 4). The 1925-88 period is divided into two periods of equal length (34 years), and the number of days occurring within each 2° F increment of the daily temperature range is determined for each period for the April-September season. Both periods show similar bimodal distributions, likely caused by two distinct weather patterns during Pacific Northwest summers (April, May, June and September tend to be more cloudy and wet, while July and August are quite dry with predominantly clear skies). There is a pronounced shift to the left in the distribution for the later period, indicating a significant decrease in the number of days in the high temperature range and an increase of days in the low range.

Further analysis of the same periods discloses a definite increase in mean temperatures for high temperature ranges (28-45° F) and a decrease in temperature for days when the range was low (Figure 5). There are a larger number of days in the lower range category at Snoqualmie Falls and the overall effect is a decrease in temperature when all days are considered. The number of days falling in the 28-45° F range each year at Snoqualmie Falls is shown in Figure 6. The decline in the number of days with "clear skies" is one of the most dramatic aspects of climate change arising from this study.

The trend in mean temperatures occurring during days when the range is from 28-45° F is shown in Figure 7. Two phenomena are noted in Figure 7: the significant increase in temperature occurring after about 1955, and a definite increase in temperature variability after this date.

Figure 8 shows the same data but plotted for just the 1955-88 period. A linear regression determined for these data show an average increase in summer temperatures of about 0.1° F per year.

Similar analyses for Aberdeen (Figure 9), Newport (Figure 10), Olga (Figure 11 and 12), and Cedar Lake (not shown) give similar results. Olga demonstrates a pattern close to that of Snoqualmie Falls, although not as pronounced. It is thought that Olga is strongly influenced by Puget Sound water temperatures (the correlation between Olga mean annual minimum temperature and Puget Sound water temperature for the 1934-83 period is +0.88). Therefore Olga's minimum temperatures are less controlled by atmospheric conditions than are those of Snoqualmie Falls.

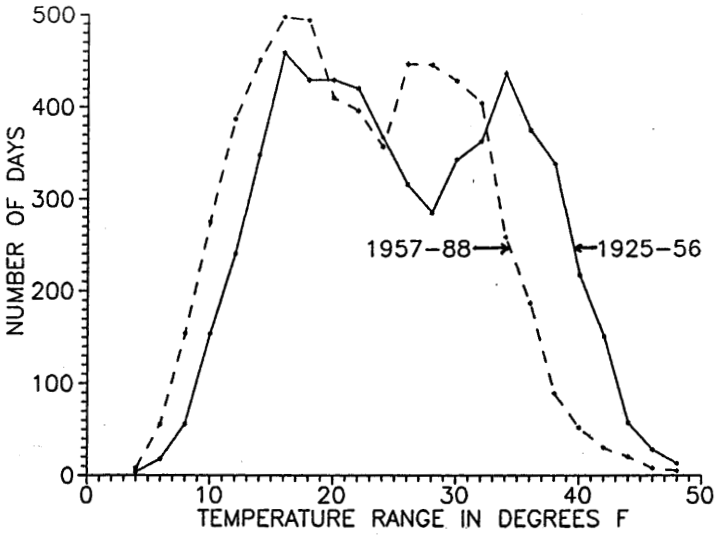

Figure 4.
***DISTRIBUTION OF DAYS OF THE DIURNAL RANGE IN TEMPERATURE** for Snoqualmie Falls for 1925-56 and 1957-88 periods.*

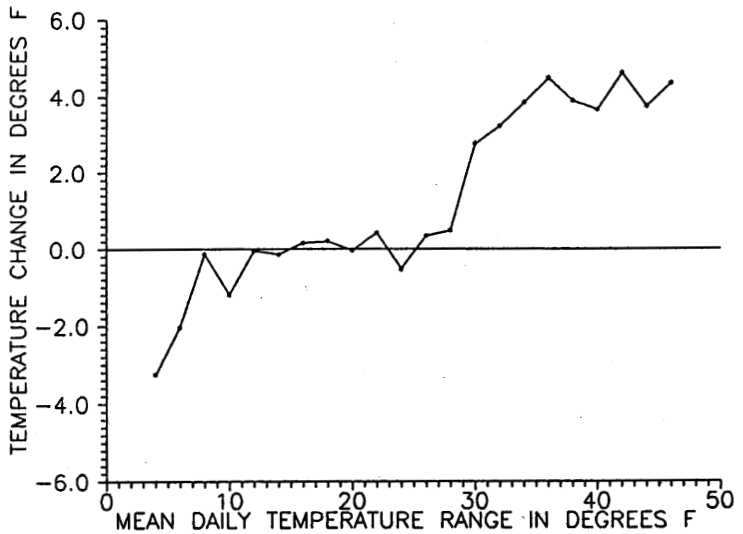

Figure 5.
***SUMMER (APRIL-SEPTEMBER) TEMPERATURE CHANGE** as a function of temperature range at Snoqualmie Falls, Washington (mean of 1957-88 minus 1925-56 periods).*

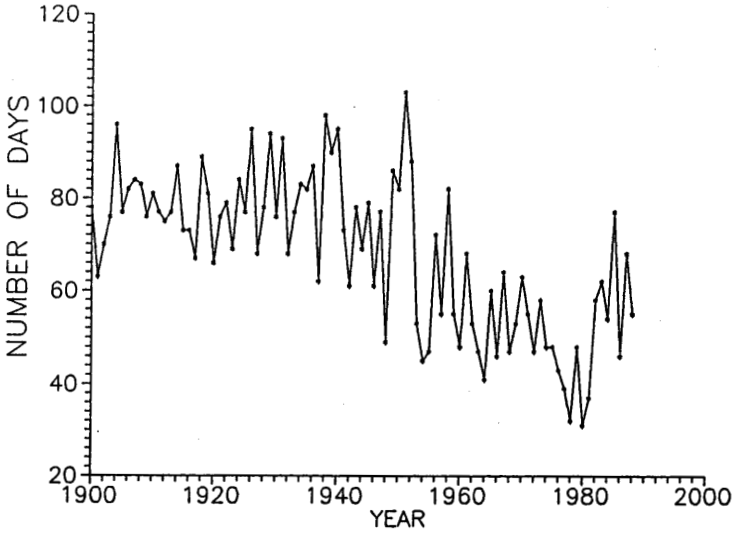

Figure 6.
NUMBER OF DAYS FALLING IN THE 28-45° F TEMPERATURE RANGE *each April-September season at Snoqualmie Falls.*

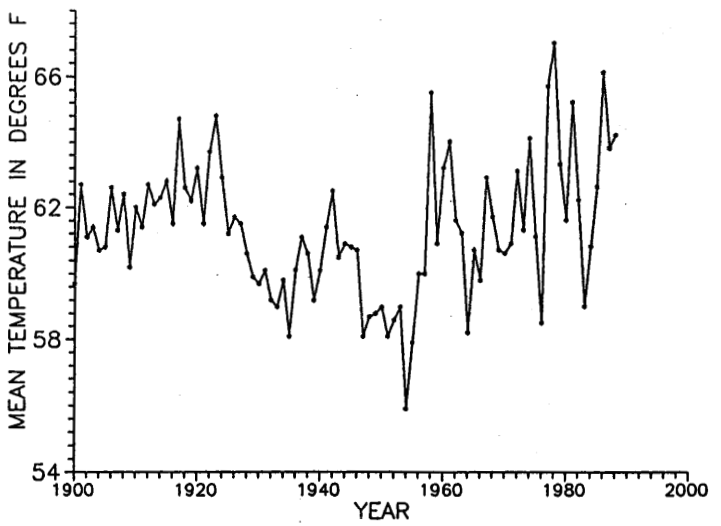

Figure 7.
MEAN SUMMER (APRIL-SEPTEMBER) TEMPERATURE AT SNOQUALMIE FALLS *for temperature range of 28-45° F., for 1900-88 period. Note that the variability appears to increase after about 1960.*

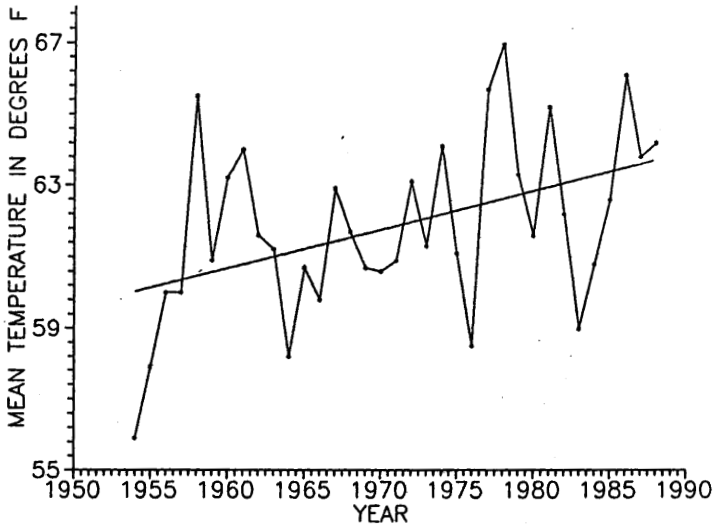

Figure 8.
MEAN SUMMER (APRIL-SEPTEMBER) TEMPERATURE AT SNOQUALMIE FALLS *for temperature range of 28-45° F., for the 1955-88 period. An increase in temperature of approximately 0.1° per year is indicated (2.9 degrees for the 34 year period).*

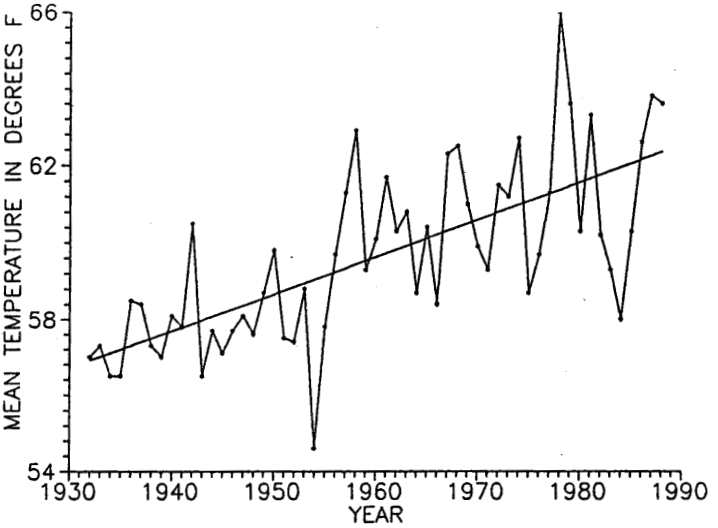

Figure 9.
MEAN SUMMER (APRIL-SEPTEMBER) TEMPERATURE AT ABERDEEN *for temperature range of 25-50° F., for the 1932-88 period. An increase in temperature of approximately 0.1° per year is indicated (6.1° F for the 57 year period).*

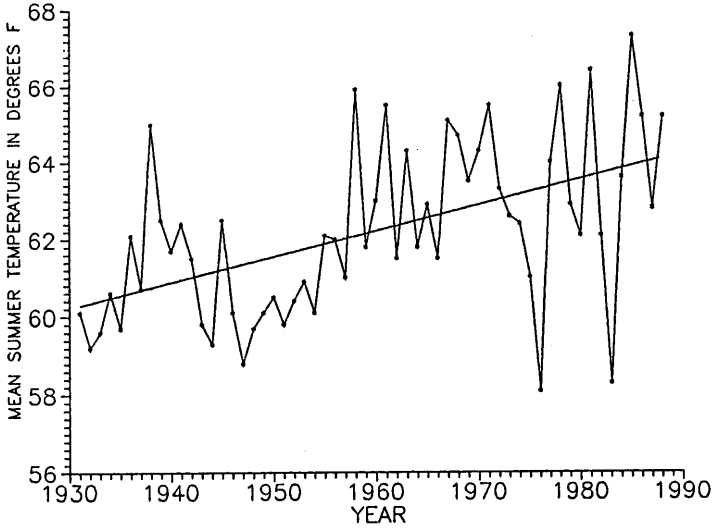

Figure 10.
MEAN SUMMER (APRIL-SEPTEMBER) TEMPERATURE AT NEWPORT FOR TEMPERATURE RANGE OF 40-60° F., *for the 1931-88 period. An increase in temperature of approximately 0.07° per year is indicated (4.0° F for the 58 year period).*

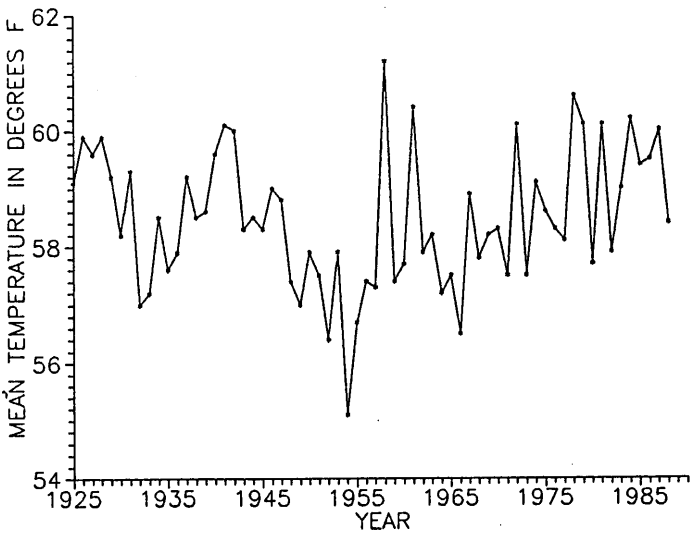

Figure 11.
MEAN SUMMER (APRIL-SEPTEMBER) TEMPERATURE AT OLGA *for temperature range of 22-36° F., for the 1925-88 period.*

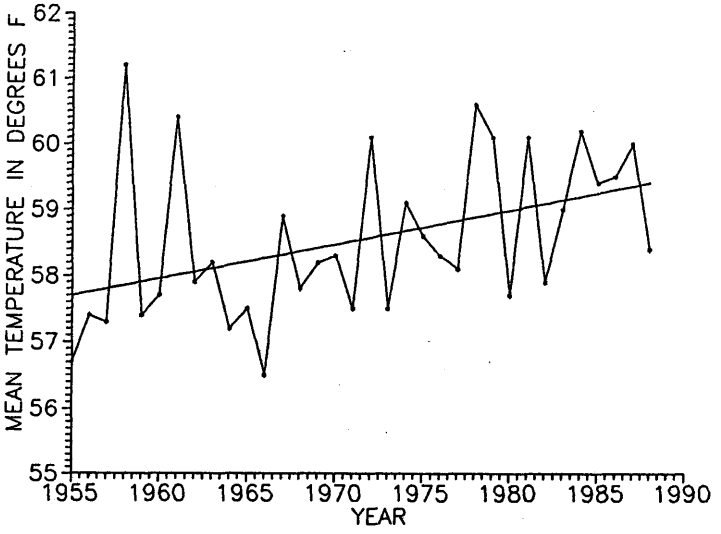

Figure 12.
***MEAN SUMMER (APRIL-SEPTEMBER) TEMPERATURE** at Olga for temperature range of 22-36° F., for the 1955-88 period. An increase in temperature of approximately 0.06° per year is indicated (2.0° F for the 34 year period).*

TEMPERATURE RANGE AND THE GREENHOUSE EFFECT

The increase in air temperatures on days of high temperature range and the decrease on days of low range since about 1955 may be due to the effect of greenhouse gases for the following reason:

The influence of greenhouse gases in the atmosphere would tend to be more pronounced on days with a minimum of clouds and haze, namely on days with a large difference between the maximum and minimum air temperature. Shortwave solar radiation reaching the earth's surface on these days would be transformed to long wave radiation at the earth's surface and re-radiated. However, the back radiation from greenhouse gases would tend to offset this radiation, causing air temperatures to rise and thus explaining the observed temperature increase on days with high ranges.

However, increased temperatures occurring over the oceans would also increase evaporation, producing greater cloudiness. The cooler temperatures observed during days of low temperature range may be due to thicker clouds and/or cloud tops with higher albedos.

TEMPERATURE VARIABILITY

The variability of temperature appears to be increasing during periods of high temperature range — in other words, both negative and positive departures from normal summer temperatures are much greater now during periods of clear weather than were occurring three decades ago.

Temperature variability can be expressed simply by the coefficient of variation:

$$CV(i) = SD(i)/TB(i)$$

where CV = Coefficient of variation for year (i),
SD = Standard deviation of TB for period (n),
TB = Mean temperature for period (n).

A running value of CV is calculated by moving the year forward in 1 year increments (i, i+1, i+2, etc.). For example, using the 1900-88 period for analysis, with n equal to 20 years, the first value of CV would be for 1919, based upon the SD and TB values calculated for the 1900 to 1919 period ((i-n) to (i)). The 1920 value for CV is based on the 1901-1920 period, the 1921 value based upon the 1902-21 period and so on, up to 1988, which is based on the 1969-88 period.

Selection of n is arbitrary but is somewhat controlled by the relative brevity of the total record. If n is too small (5 years) the values of SD and TB are erratic and not meaningful. If n is large (50 years), the remaining record is too short to reveal trends. As a compromise between these two controls, a value of 20 years was used in this study.

The variability (year to year fluctuations) of Snoqualmie Falls temperature shows a definite increase around 1955, as illustrated in Figure 7. A plot of the percent coefficient of variation, calculated with a 20 year running mean for the 1900-88 period, shows a very sharp increase in the late fifties and a continued elevated value since then (Figure 13). Similarly, the variability in the number of days in the 28-45° F range has increased at Snoqualmie Falls (Figure 14). Temperature variability also increased during the 1950s at Cedar Lake (Figure 15), Aberdeen (Figure 16) and Newport (Figure 17). An average of CV for Snoqualmie Falls, Olga, Cedar Lake, Aberdeen and Newport (Figure 18) shows a pronounced increase in CV occurring in 1959, with the higher value being maintained through 1988.

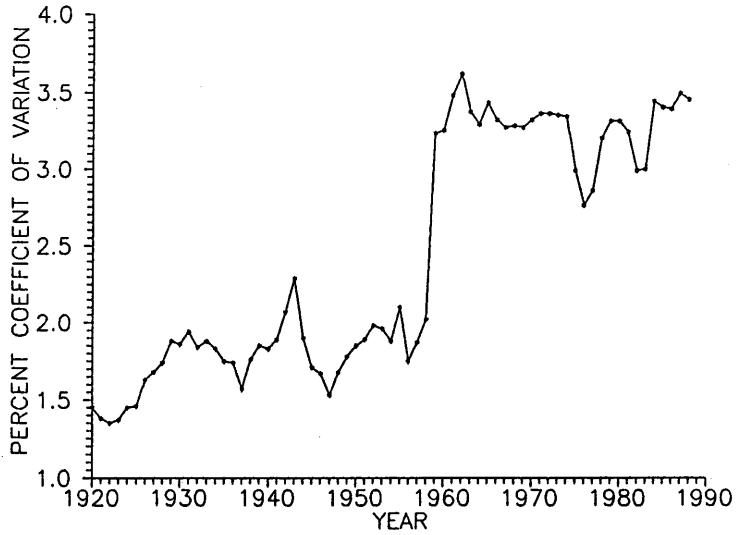

Figure 13.
VARIABILITY OF SNOQUALMIE FALLS MEAN SUMMER TEMPERATURE *for 28-45° temperature range, given as percent coefficient of variation for a 20 year running mean.*

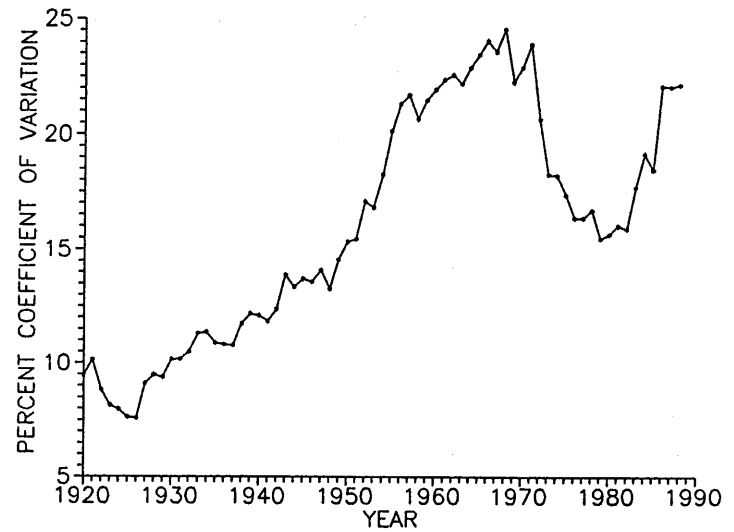

Figure 14.
VARIABILITY OF NUMBER OF DAYS *in the 28-45° temperature range at Snoqualmie Falls, given as percent coefficient of variation for a 20 year running mean.*

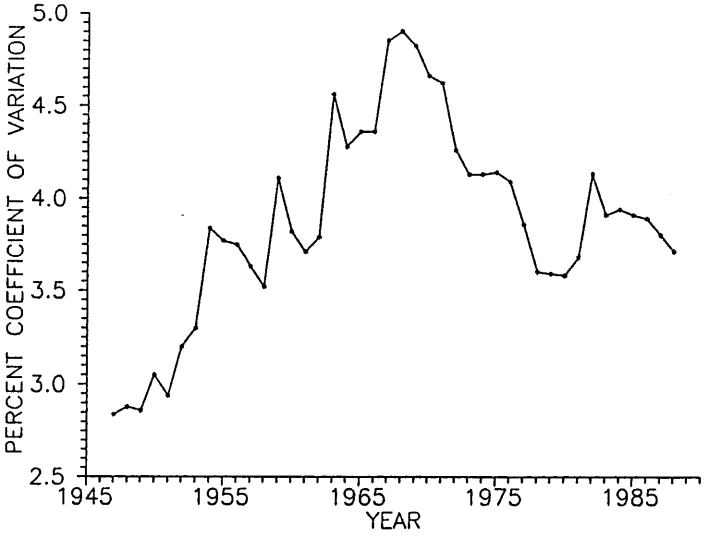

Figure 15.
VARIABILITY OF CEDAR LAKE MEAN SUMMER TEMPERATURE *for the 30-45° temperature range, given as percent coefficient of variation for a 15 year running mean.*

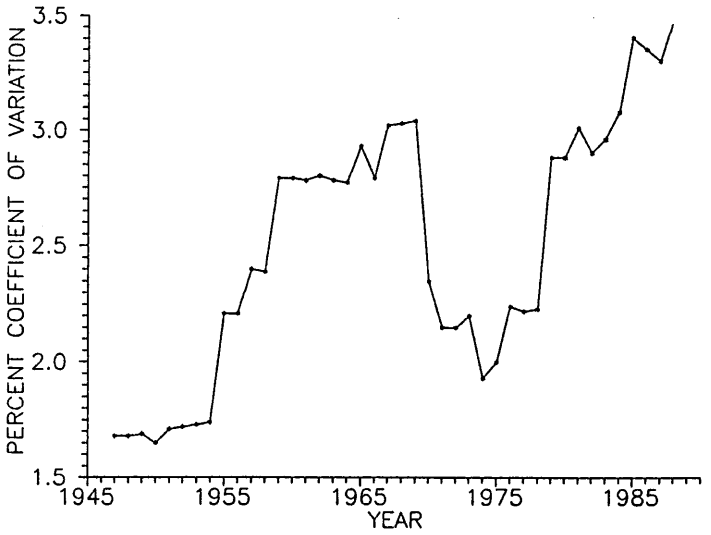

Figure 16.
VARIABILITY OF ABERDEEN MEAN SUMMER TEMPERATURE *for the 22-48° temperature range, given as percent coefficient of variation for a 15 year running mean.*

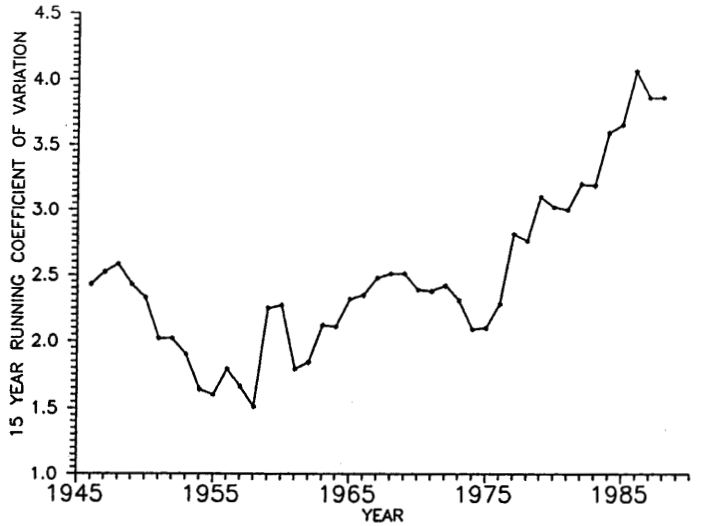

Figure 17.
VARIABILITY OF NEWPORT MEAN SUMMER TEMPERATURE *for the 30-60 ° F temperature range, given as percent coefficient of variation for a 15 year running mean.*

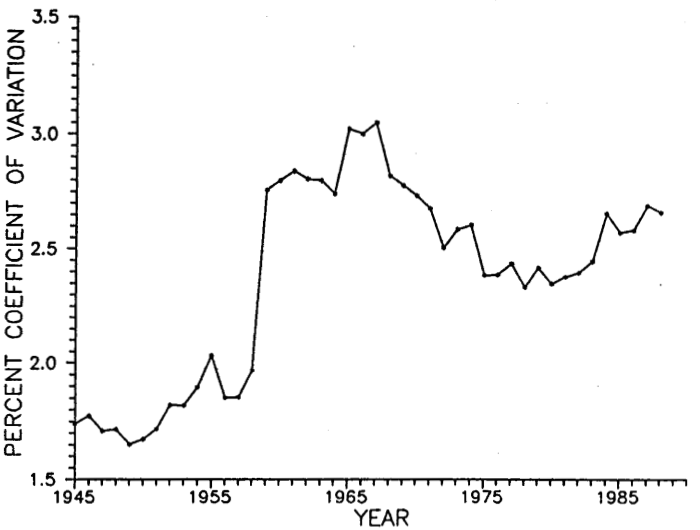

Figure 18.
VARIABILITY OF MEAN SUMMER TEMPERATURE *at higher temperature ranges, expressed as the percent coefficient of variation averaged for Snoqualmie Falls, Olga, Cedar Lake, Aberdeen and Newport.*

CONCLUSIONS

1. Significant temperature increases have occurred in the Pacific Northwest during days of high temperature range (clear skies), mainly since about 1960. The increase is about 0.1° F per year, or 10° F (5.5° C) per 100 years, an order of magnitude greater than that shown for all days.
2. During this same period, the temperature has decreased during days of low temperature range (cloudy days), although much less than the high range increase.
3. The increase in temperature during clear weather coincides with an accelerated increase in atmospheric carbon dioxide.
4. The number of days with a high temperature range is decreasing (more cloudiness is occurring).
5. The climate of the Pacific Northwest suddenly became more variable in the late 1950s.

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PUGET SOUND

RESEARCH '91

MEASURING PUGET SOUND–I (PSAMP)

Session Co-chairs:

John W. Armstrong, U.S. Environmental Protection Agency,
and Andrea E. Copping, Puget Sound Water Quality Authority

INTRODUCTION

John W. Armstrong[1]

Monitoring, *per* the Puget Sound Ambient Monitoring Program, is repeated measurements, at the same location, at specific frequencies, for a long period of time. The goals of this monitoring for a long period of time are first of all to determine existing conditions in the Sound. Are sediments toxic, for example? Second of all, is to determine trends. Are contaminant levels in the fish in the Sound going down, going up, or remaining the same? And then lastly, to allow us to determine the consequences of management actions in the Sound. For example, will fencing cattle from streams in part of the Sound improve water quality? Or, on a broader scale, is the whole Puget Sound Water Quality Management Plan working?

Until recently, monitoring the Sound has consisted of generally small, short-term, uncoordinated, and generally poorly recorded projects. But during the past few years, with the documented pollution problems growing in the Sound, and with our accelerating population growth, there has been a broad realization that a long-term integrated monitoring program with an annual summary report is sorely needed. This realization led to the Puget Sound Ambient Monitoring Program (PSAMP) that we have today.

PSAMP evolved from a NOAA report in 1985. NOAA came out with a report that documented existing programs and suggested a broad, integrated program for the Sound. In 1986, EPA commissioned a report that built on the NOAA study but tried to make the monitoring program a more manageable piece of work, to reduce it somewhat, and to seek input from state and federal agencies and the interested public. In 1986 the Puget Sound Water Quality Authority also wrote an issue paper, called "Comprehensive Monitoring of Puget Sound," that showed [a monitoring program] was definitely needed. This issue paper led to the inclusion, in the 1987 Puget Sound Water Quality Management Plan, of a component for developing and implementing a Puget Sound Ambient Monitoring Program. Finally, the Water Quality Authority and its committees took this EPA draft report on monitoring and, working very closely with the state agencies who would do that monitoring, came out with a final PSAMP report in 1988.

Today, while several parts of that monitoring Program have been initiated, the funding for the whole program is lacking. But on the bright side, it has been initiated, and the state agencies are working very well together.

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In this session we will hear about what is included in PSAMP, what the programs are, what we have learned about the Sound to date from those components of the Monitoring Program, how the information and data being collected are being managed, and finally, what role citizens are having in that Monitoring Program.

THE PUGET SOUND AMBIENT MONITORING PROGRAM: HISTORY AND PERSPECTIVE

Andrea E. Copping[1] and John W. Armstrong[2]

INTRODUCTION

The Puget Sound Ambient Monitoring Program (PSAMP) is a coordinated, comprehensive monitoring program which examines environmental variables throughout Puget Sound and the surrounding watersheds. The development, implementation, management, and coordination of PSAMP can serve as an excellent model for estuarine monitoring programs nation-wide. PSAMP was developed between 1986 and 1988, and began its first year of data collection in 1989. PSAMP is the monitoring program of the Puget Sound Estuary Program (PSEP). This paper describes the steps involved in the development of PSAMP, the goals of the program, and the monitoring design.

DEVELOPMENT OF PSAMP: INSTITUTIONAL ARRANGEMENTS

In developing PSAMP, it became clear that interaction of all affected parties is essential in the successful development of an estuarine monitoring program. Identification of the key resource agencies, interactions among the affected parties, costs, development schedules, and implementation phasing will all be discussed to explain the development and initial implementation of PSAMP.

The Puget Sound Water Quality Authority (PSWQA)

In 1985, the Washington State legislature created the PSWQA as a state agency. The enabling legislation charged the PSWQA with developing a comprehensive management plan for Puget Sound and its related waterways. The legislation required that the plan include consideration of many issues, including "...recommendations for a comprehensive water quality and sediment monitoring program..."

PSWQA Monitoring Issue Paper

As part of the development of the 1987 Puget Sound Water Quality Management Plan, the PSWQA wrote an issue paper on Comprehensive Monitoring of Puget Sound (PSWQA, 1986). The issue paper reviewed existing Puget Sound monitoring programs, described the process for developing a comprehensive

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water quality and sediment monitoring program which includes biological resources, and presented alternatives for developing the monitoring program (Table 1).

Table 1.
ALTERNATIVES FOR IMPROVING PUGET SOUND MONITORING

- Development and adoption of standardized protocols
- A centralized or coordinated data management system
- Improved data interpretation/report preparation and information dissemination
- Adequate laboratory capacity
- Review of existing water column program and changes to collect more pertinent information. Follow up actions could be tied to monitoring results.
- Development of a sediment monitoring program, including ambient sediment monitoring, intensive surveys, discharge monitoring, and dredging/dredged material disposal monitoring
- Improved point and nonpoint source monitoring for municipal treatment plants and industrial facilities, searches for illegal discharges
- Greater number of intensive surveys to identify sources of pollution
- Development of a biological monitoring program
- Improved monitoring of commercial and recreational shellfish beds
- Monitoring by citizen volunteers

Reference: PSWQA, 1986.

The issue paper identified four major components of a comprehensive monitoring program:

- ambient (or background) monitoring
- discharge monitoring/compliance monitoring
- intensive surveys (such as a detailed look at an embayment)
- resource monitoring (e.g. abundance of shellfish, benthic community health, changes in shoreline and habitat, weather, demographics, and socioeconomic information.)

The PSWQA included findings of the 1986 issue paper, and comments received on the issue paper, in the 1987 Puget Sound Water Quality Management Plan. The goal of the monitoring program was to develop and implement a comprehensive environmental monitoring program for Puget Sound.

EPA Region 10 Monitoring Guidance Report

In 1986, the Office of Puget Sound, EPA Region 10, directed a consultant to develop a monitoring strategy for a Sound-wide monitoring program. Through a process involving consultation with agencies concerned with Puget Sound management, as well as university scientists and the public, the consultant

developed a monitoring design which included goals and objectives, sampling design, operation of the program, and methods for sampling, analysis, and reporting of data. The monitoring design was released in draft form in 1986 (Tetra Tech, 1986). At that point EPA Region 10 and the PSWQA recognized the need for a process which would rely more directly on the many agencies, organizations, and individuals with an interest in Puget Sound monitoring.

Monitoring Management Committee

The 1987 plan required the PSWQA to appoint a Monitoring Management Committee (MMC) (PSWQA, 1987). The MMC is chaired by the PSWQA and consists of representatives of state, federal, local, and tribal governments, business, industry, shellfish growers, university scientists, Canadian agencies, environmental groups, and the public. The plan directed the MMC to develop a comprehensive ambient monitoring program, and to address a number of specific issues related to the program, including data needs of Puget Sound plan programs, the design of the monitoring program and data management system, and funding mechanisms for the program (PSWQA, 1987). The PSWQA provided staff support to the MMC to carry out coordination and data management tasks.

The committee began its work in late 1986 by defining the goals and objectives of the monitoring program and then proceeded to review and modify the consultant-prepared monitoring strategy (Tetra Tech, 1986). The MMC established 13 technical subcommittees to study the monitoring design and to make recommendations on program design. Subcommittees included: habitat, shellfish, nutrient/phytoplankton, bioassay, data systems, institutional, and others.

From late 1986 to early 1988 the MMC refined the monitoring program design which included sampling and analysis recommendations, a data management system design, quality assurance guidelines, reporting requirements, cost estimates, and funding alternatives. The committee released a draft program design in May 1987 for public and scientific peer review. Workshops were held for the public, local government, and tribal staff. Comments received from the PSEP technical advisory committee (TAC), scientists, agency staff, and other affected parties were considered by the committee and a final report entitled "Puget Sound Ambient Monitoring Program - Detailed Design Considerations" was adopted by the PSWQA and published in April 1988 (PSWQA, 1988a). The report included PSAMP goals and objectives, and sampling and analysis strategies for monitoring sediment quality, marine and fresh water quality, fish, shellfish, birds, marine mammals, river mouths, nearshore habitat, and additional data.

Cost of PSAMP

A technical subcommittee to the MMC (Costing Subcommittee), PSWQA staff, and a consultant retained by PSWQA worked to develop a cost estimate for PSAMP. In 1987 dollars, full implementation of PSAMP was calculated to cost approximately $3.2 million a year, with startup costs of $250,000 to $350,000 over the first two years. Early in 1988 it became apparent that state funds would not be available for full implementation of the program. Through a priority-setting process involving the MMC and other scientists, a plan for phased implementation of the program was devised. This process established the order in which PSAMP tasks would be funded when implementation funding became available. The MMC established sediment quality, fish tissue, and shellfish tissue monitoring as top-ranked priorities for funding. The MMC also recognized that agency staff could not manage to fully implement PSAMP in a single year, even if funds were to become available, due to workload.

The development phase of PSAMP, including establishment of the data management system, has been funded largely by PSEP funds. State, federal, local, and tribal agencies, as well as private sector funds, have contributed individuals' time to serving on monitoring committees and subcommittees. The development costs of PSAMP from 1987- 1989 were approximately $200,000.

Funding

Long-term stable funds for monitoring programs are notoriously difficult to secure. Funding for four types of activities were needed to assure the success of PSAMP: development of the draft monitoring strategy and workshops by contractor; staff time for program development; startup costs; and ongoing implementation. As previously noted, EPA Region 10 funded the initial program development and provided PSEP funds for PSWQA staff to coordinate the full development of PSAMP and the data management system. PSEP resources continue to fund PSWQA staff to begin program implementation and further database development through FY91.

To date, approximately 30% of PSAMP has been funded, including central coordination and data management tasks. Other than PSEP funds available through EPA, all PSAMP funding has come from the state of Washington. Like all Puget Sound Water Quality Management Plan funds, PSAMP funds are given directly to the implementing agency; the PSWQA submits a funding request for the entire plan, with assistance from the other agencies, and acts as an advocate for the plan to the Governor and the state legislature.

During 1989-90, PSAMP received approximately $900,000 of state general fund money each year (PSWQA, 1990a). The Washington State Department of Ecology receives $500,000 a year for sediment sampling and analysis. $200,000

goes to the Washington State Department of Fisheries for measuring toxics in bottom fish and recreational fish tissue and for bottomfish health assessments. The Washington State Department of Health uses $160,000 for sampling and analysis of shellfish tissue for bacterial and/or chemical contamination. The PSWQA receives $40,000 a year for coordination and data management. $50,000 in citizens' monitoring activities are funded by a special fund for public involvement and education (PIE Fund) from the state Centennial Clean Water Fund (tax on tobacco products). In addition to securing new funds, the Washington State Department of Ecology has modified existing marine and fresh water monitoring programs to meet PSAMP goals, saving PSAMP $245,000 a year.

Initial PSAMP Assignments

Agencies represented on the MMC were asked to express their interest in playing a lead role in specific tasks of PSAMP. "Implementing agencies" were chosen for each PSAMP task, based on these expressions of interest. It came as no surprise that the agencies that expressed interest in becoming implementing agencies were those with regulatory and/or management responsibilities as well as expertise in the specific areas; initially all implementing agencies are state agencies (Table 2), although this could change in the future. Each implementing agency was responsible for preparing a detailed implementation plan, managing their specific PSAMP task, quality assurance and quality control, data management and reporting, and transfer of PSAMP data to the central database housed at the PSWQA. The MMC felt strongly that the PSWQA should continue to play the lead role in coordinating PSAMP and providing data management functions, as the Authority has both the expertise and staff available to carry out these functions.

Table 2
PSAMP TASK ASSIGNMENTS BY AGENCY.

Monitoring Task	Implementing Agency
Sediment Quality	Washington Department of Ecology
Marine Water Column	Washington Department of Ecology
Fish	Washington Department of Fisheries
Shellfish	Washington Department of Health
Birds	Washington Department of Wildlife
Marine Mammals	Washington Department of Wildlife
Nearshore Habitat	Washington Department of Natural Resources
Freshwater	Washington Department of Ecology

Reference: PSWQA, 1990a

Management of PSAMP

The management structure for PSAMP consists of the PSAMP Steering Committee, the MMC and subcommittees, and the PSWQA board. PSWQA staff provide technical and administrative support to the committees, and chair the MMC and PSAMP Steering Committee.

As PSAMP moved from the development to the implementation stage, it became apparent that the MMC was too large and unwieldy a group to coordinate the program and make day-to-day decisions. In addition, some state agencies were uncomfortable with having representatives from the private sector make decisions involving the use of public funds. To solve these problems, a second monitoring committee was formed, the PSAMP Steering Committee.

The PSAMP Steering Committee is chaired by the PSWQA and is made up of one representatives from each of the five implementing agencies, the PSWQA, EPA Region 10, local government, and tribal government. Additional members can be added in future if necessary. The committee is responsible for the overall coordination and management of PSAMP. The PSAMP Steering Committee meets once a month and reaches decisions by consensus.

Should the PSAMP Steering Committee be unable to reach consensus on technical or other program matters, or should any member be dissatisfied with decisions made by the committee, the matter can be referred to the PSWQA board for resolution.

The MMC maintains the same representation that it had during the development phase, and, with its subcommittees, acts as the advisor to the PSAMP Steering Committee. The MMC meets twice a year or as needed. Major changes in PSAMP design, changes in assignment of an implementing agency, setting funding priorities, and other technical issues must be referred to the MMC by the PSAMP Steering Committee.

Maintaining current PSAMP funding and securing additional funds is a major focus of the PSAMP Steering Committee and the PSWQA. The monitoring committees and the PSWQA are relying heavily on legislative advocacy, attention from the media, and garnering of public support through the dissemination of PSAMP results to aid in securing PSAMP funds.

Additional Monitoring Studies

Monitoring programs and studies that evaluate environmental conditions and potential contamination sources in the Puget Sound region that are of interest to PSAMP include:

- nonpoint source control watershed monitoring
- Puget Sound Dredge Disposal Analysis (PSDDA)
- PSEP Urban Bay Studies (UBATs)
- NPDES compliance monitoring
- Department of Ecology intensive surveys (tracing sources of contamination)
- NOAA National Status and Trends Program
- climate/weather data.

Assuring PSAMP Implementation

In order to ensure that PSAMP would be implemented as planned, the PSWQA negotiated memoranda of agreement (MOA) with each of the implementing agencies. These agreements detailed the specific responsibilities of each implementing agency and the PSWQA in relation to PSAMP. The MOAs specify that each implementing agency must carry out its responsibilities under the PSAMP design, must maintain PSAMP funding levels within the agency unless the Governor or the state legislature requires across-the-board agency funding cuts, and must refer changes in PSAMP to the PSAMP Steering Committee for approval. Through the MOAs, the PSWQA agrees to provide staff support to the PSAMP committees and to work with the implementing agencies to maintain long-term funding for PSAMP.

During the 1990 state legislative session, the PSWQA enabling legislation was amended to address the need to implement PSAMP. A new section was added to the legislation dealing with PSAMP. This section requires the implementing agencies to participate in the program, requires the PSWQA to ensure implementation of PSAMP, and allows the PSWQA to establish an interagency committee to coordinate PSAMP.

Review of PSAMP

The PSAMP Steering Committee and the MMC recognize that the long-term success of PSAMP rests on making the program effective in answering needs of the resource management agencies, and in informing the public of the state of the Sound, within the available budget. An annual review of PSAMP is built into the process by the participants in order to keep the program focussed on top priority monitoring needs and to ensure the efficient use of funds. The first annual review will begin in late 1990. In addition, PSAMP will undergo periodic independent review. The independent review will be more extensive than the annual review and will examine the statistical validity of PSAMP results, and the degree to which PSAMP data are being used in management decisions. The first independent review is set for 1994, with subsequent reviews every 3 years.

THE PUGET SOUND AMBIENT MONITORING PROGRAM

Program Goals

The MMC developed five goals for PSAMP:

1) Characterize and interpret spatial and temporal patterns of conditions of Puget Sound as they affect natural resources and humans, and recognize contamination.
2) Take measurements to support specific program elements identified in the Puget Sound Water Quality Management Plan.
3) Measure the success of programs implemented under the Puget Sound Water Quality Management Plan.
4) Provide a permanent record of significant natural and human-caused changes in key environmental indicators in Puget Sound over time.
5) Support research activities through the availability of consistent, scientifically valid data.

In order to achieve these goals, the monitoring program characterizes and interprets spatial and temporal patterns for the following:

- factors that endanger human health
- biological populations and communities
- factors affecting biological populations
- presence of pollutants in the Sound
- entry of pollutants into the Sound from rivers and streams
- estuarine and wetland habitats
- results of water quality degradation, such as shellfish bed closures
- improvements in water quality such as the reopening of shellfish beds
- factors that affect aesthetic conditions.

The monitoring program identifies areas where:

- resources are damaged or contaminated
- resources or conditions are changing over time
- intermittent or periodic degradations are occurring.

The Scope of PSAMP

The design of PSAMP calls for monitoring of sediments, water quality in marine and fresh waters, fish, shellfish, birds, marine mammals, and nearshore habitat. The focus of the program is Puget Sound-wide, which includes Hood

Canal, portions of the Straits of Juan de Fuca and Georgia to the Canadian border, and the surrounding watersheds. Sampling occurs year-round. Station locations, the number of stations or surveys, and the timing of sampling varies with each type of measurement. Three types of stations are sampled in many tasks of the program:

- fixed stations that are sampled each year,
- rotating stations that are sampled on a 3 year cycle; these stations can provide extended geographic coverage, and
- a small number of floating stations that are located at the discretion of the implementing agency; these stations can provide additional geographic coverage,
- or allow investigation of a suspected water or sediment quality problem.

Table 3 summarizes the design for full PSAMP implementation, as well as the monitoring data that are being collected during 1989-90.

Citizens' monitoring is an integral part of PSAMP. The advantages of using citizens to collect data are twofold: samples and observations can be collected in a cost-effective manner, particularly at remote locations where travel by agency staff is costly; and as a tool for increased public involvement, education, and stewardship. Citizens' groups provide volunteers to collect information and samples under the guidance of implementing agency staff (state PSAMP funds are used for administrative purposes and to reimburse expenses). The PSAMP Steering Committee has carefully chosen parameters for collection by citizen monitors to minimize quality assurance problems; for example, citizens are used extensively to dig shellfish for tissue analysis, to catch marine fish and salmon for tissue analysis, and to groundtruth remote sensing data.

Data Management, Quality Assurance and Reporting

Data management and quality assurance/quality control (QA/QC) requirements for PSAMP were designed as integral parts of the program. The data management system consists of a central database housed at the PSWQA, and agency databases at each of the implementing agencies. The databases are microcomputer (desktop computer) based, and exchange data electronically using a set of standardized data transfer formats developed by PSWQA staff and technical subcommittees to the MMC. The central database and several of the agency databases are on dBase 4 and have been customized by PSWQA staff.

PSAMP is developing a geographic information system (GIS) on Puget Sound in order to display and analyze PSAMP data geographically. Resource maps

from the previously completed Puget Sound Environmental Atlas (Evans-Hamilton and D.R.Systems, 1987) have recently been converted from graphics files to Arc-Info (GIS program) by the USGS, under an agreement with the PSWQA. PSWQA staff are presently working with the Washington State Department of Natural Resources to update the Atlas on GIS and will complete the initial Puget Sound GIS by 1993.

Each implementing agency is responsible for quality assurance/quality control (QA/QC) of sample collection, analysis, and data management for their tasks of PSAMP. Limited QA/QC of data are performed at the PSWQA before data are accepted into the central database. QA/QC guidelines were established by the MMC and are detailed in each agency's implementation plan.

Each implementing agency is required to prepare an annual technical report detailing their PSAMP monitoring over the previous year. Using the agency technical reports and other program information PSWQA staff prepare an integrated PSAMP report for public release each year. The first of these reports, titled *Puget Sound Update*, was released in May 1990 (PSWQA, 1990b). PSAMP reports and quality assured data are available through the PSWQA.

Keys to Success

The greatest credit for the success of PSAMP design process must go to the agencies and individuals who saw the need for a comprehensive monitoring program and who made the commitment to make the process work. The PSWQA played an essential role in coordinating and managing the process. One key to the PSWQA's past and ongoing successes has been the agency's comprehensive approach to complex issues by simultaneously addressing the scientific, resource management, political, and public concerns. PSWQA staff have spent considerable effort trying to balance these often conflicting pressures. The PSWQA has been able to maintain an objective role in managing and coordinating PSAMP without competing with the individual agencies; the PSWQA does not carry out any sampling operations.

EPA Region 10 has supported the development of a number of products and studies which have laid the groundwork for PSAMP, including the Puget Sound Protocols and Guidelines; the Puget Sound Environmental Atlas; reconnaissance studies for sediment and tissue contamination; seafood risk assessment study; and the Puget Sound chemicals of concern matrix.

The design and initial implementation of PSAMP, including the data management system, is successful both as a technical product and for the consensus process from which it came. The involvement of representatives from both the public and private sectors, a targeted outreach effort, and the process of peer review have all contributed to the success with which the program has been received by the implementing agencies. The data management system

Table 3.
PSAMP DESIGN AND 1989-90 ACTIVITIES

Task	Task Subcomponents	Proposed No. of Stations/Surveys	Actual 1988-89 Stations/Surveys	Proposed Sampling Frequency	Actual Sampling Frequency
Sediment quality	Sediment chemistry Bioassays Benthic invertebrates	75 throughout Puget Sound	50 throughout Puget Sound	Annually-spring	March-April (1989, 1990)
Marine water column	Long-term trends	10-12 throughout Puget Sound	24 throughout Puget Sound	Monthly	Monthly
	Known water quality problems	5-10 in selected bays			Seasonally
	Algal growth	5-10 in selected bays			Summer/winter solstices
Fish	Tissue chemistry (bottomfish)	21 stations	10 stations	Annually-early summer	May 1989
	Liver histopathology (bottomfish)	21 stations	10 stations	Annually-early summer	May 1989
	Tissue chemistry (cod, rockfish, salmon)	5-10 stations	4 stations	Annually, depending on species	September/February/ April 1989-1990
Shellfish	Abundance Bacterial contamination Tissue chemistry Paralytic shellfish poisoning	35 beaches 35 beaches 35 beaches 35 beaches	10 beaches 10 beaches 4 beaches 16 beaches	Annually Quarterly Annually Monthly	May 1990 Quarterly April 1990 Monthly
Birds		Throughout Puget Sound	No activity	Monthly, annually	
Marine mammals		Throughout Puget Sound	No activity	Monthly, annually	
Nearshore habitat		One-third of Puget Sound	No activity	Annually	
Freshwater		75 throughout watershed	75 throughout watersheds (limited parameters)	Monthly	Monthly

Reference: PSWQA 1990b.

and data transfer formats have been very well received by state and local agencies. PSWQA staff has had numerous requests for information, and interest in PSAMP has been communicated from several of the established and emerging estuary programs around the country, as well as from other state programs, other regions, and from Canada.

The GIS recommendation was initially prepared to serve many purposes. Funding constraints now and in the future have necessitated that the effort be reduced to fit the immediate needs of updating of the Puget Sound Atlas and providing some geographic data management for PSAMP.

The redirection of existing state agency funds and the procurement of new state money for PSAMP were also aided by the long consensus process that was followed. Although sufficient state funds for full implementation of PSAMP are not currently available, almost $1 million a year is currently committed to PSAMP, and additional resources can be expected to follow in the future.

The establishment of a successful citizens' monitoring program benefits both PSAMP, through cost-effective collection of data, and educational and public involvement needs. Encouraging an educated and involved public is key to providing support and commitment to the long-term funding of PSAMP.

Opportunities to Improve Future Monitoring Programs

Throughout the many successes of PSAMP design and initial implementation, there were setbacks, minor difficulties, and areas for future improvement. The majority of these problems could be alleviated in other programs with a combination of lessons learned from this program and the addition of more staff time.

Questions have arisen during the design and initial implementation phases of PSAMP as to whether it would have been preferable to design a more limited and affordable ambient monitoring program, rather than the necessary and sufficient program designed to meet the goals set out in the MMC final report (PSWQA, 1988a). A smaller program would have been designed somewhat differently, and would not have raised the expectations of all those eagerly awaiting PSAMP data. The design of PSAMP as a thoroughly adequate program for characterizing Puget Sound and measuring the success of source control and remedial action programs will act as the blueprint with which to direct funds as they become available. The danger in designing a less comprehensive program is a level of complacency among funding sources and managers who feel that we are collecting adequate information on Puget Sound. With benefit of hindsight, we would probably design much the same program again.

It has proved to be very important to have a full-time manager/coordinator and a systems analyst to staff PSAMP. Staff have been essential for keeping all the implementing agencies and other participants informed of progress, resolving disputes and misunderstandings, carrying out technical and administrative duties, coordinating with other closely related monitoring and research programs, and publicizing the existence and results of the program.

At times technical questions brought to the MMC and PSAMP Steering Committee could not be adequately resolved due to the lack of technical expertise on the committees. Technical subcommittees were formed and proved useful for many questions; however, inadequate PSWQA staff time did not allow for sufficient meetings and contacts to resolve every need. In addition, insufficient time and attention frequently was given to the program by committee members. In some instances additional PSWQA staff time could have improved the situation, but in general there needs to be a strong devotion to the program by some of the participants, especially the implementing agencies. It is also important to recognize that there is only a finite pool of Puget Sound scientists and managers available to participate on a regular or frequent basis in such programs; a similar-sized pool of experts may prove limiting in many areas.

The major activity which was given short shrift during the initial implementation of PSAMP, and which future projects should strive to improve upon, was the publicizing of monitoring data, results, expectations, and interpretations. Even with a very limited amount of new monitoring data, there are ample historical Puget Sound data residing in the state and federal agency files which could be resurrected, compared to recently collected information, and displayed to managers and the public. Publicly releasing results and interpretations of scientific findings helps to raise the level of awareness and support for a program like PSAMP.

CONCLUSIONS

The purpose of this paper was to describe the process by which agencies, the private sector, scientists, and public interest groups interacted to form PSAMP, and to look at some of the ingredients that have made it a successful process, as well as to point out opportunities that other estuary programs could seize in order to improve upon their monitoring programs.

Puget Sound managers have learned a great deal about the process for creating a comprehensive and coordinated estuarine monitoring program which has broad-based support. The next challenge for PSAMP is to capture sufficient long-term funding to fully implement the program. The real value of PSAMP will be realized in future when management decisions based on

PSAMP information show further understanding of the Puget Sound ecosystem and increased protection of natural resources.

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PUGET SOUND MARINE SEDIMENT QUALITY, OR HOW DIRTY IS PUGET SOUND?

Peter Striplin [1], Betsy Striplin [2], and Karen Keeley [3]

INTRODUCTION

The first Puget Sound Water Quality Management Plan called for the establishment of an ambient monitoring program in Puget Sound (PSWQA, 1987). The sediment quality task of the Puget Sound Ambient Monitoring Program (PSAMP) is implemented by the Ambient Monitoring Section of the Washington Department of Ecology. In the first year, Ecology contracted the work to Tetra Tech, Inc. of Bellevue WA, and subsequently is undertaking the work in-house after the 1989 contract expired.

The purpose of the sediment quality task is three-fold: provide a baseline record of the condition of Puget Sound sediments in ambient or uncontaminated areas; aid in the identification of reference areas or values; and provide data for use by other researchers. The experimental design of the program is an integrated effort that includes the study of benthic macroinvertebrate communities, sediment toxicity and sediment chemistry.

The study area extends from Semiahmoo Bay and the Straits of Georgia in northern Puget Sound, to Port Angeles in the Strait of Juan de Fuca, and through Hood Canal, the main basin of Puget Sound and southern Puget Sound. A total of fifty stations were selected for annual sampling (Figure 1). The majority of stations were located along the 20 meter depth contour because benthic abundance and diversity are greatest at this water depth (Stober and Chew, 1984). Six of the stations were located at the centers of the Puget Sound basins at water depths exceeding 150 meters. Nichols (1985) showed that these basins, even though located away from anthropogenic activity, experienced major changes in benthic community structure.

METHODS

Sample Collection

Sediment samples were collected in March 1989 from the R/V Kittiwake using a stainless steel 0.1 m^2 double van Veen grab sampler. Sample equipment

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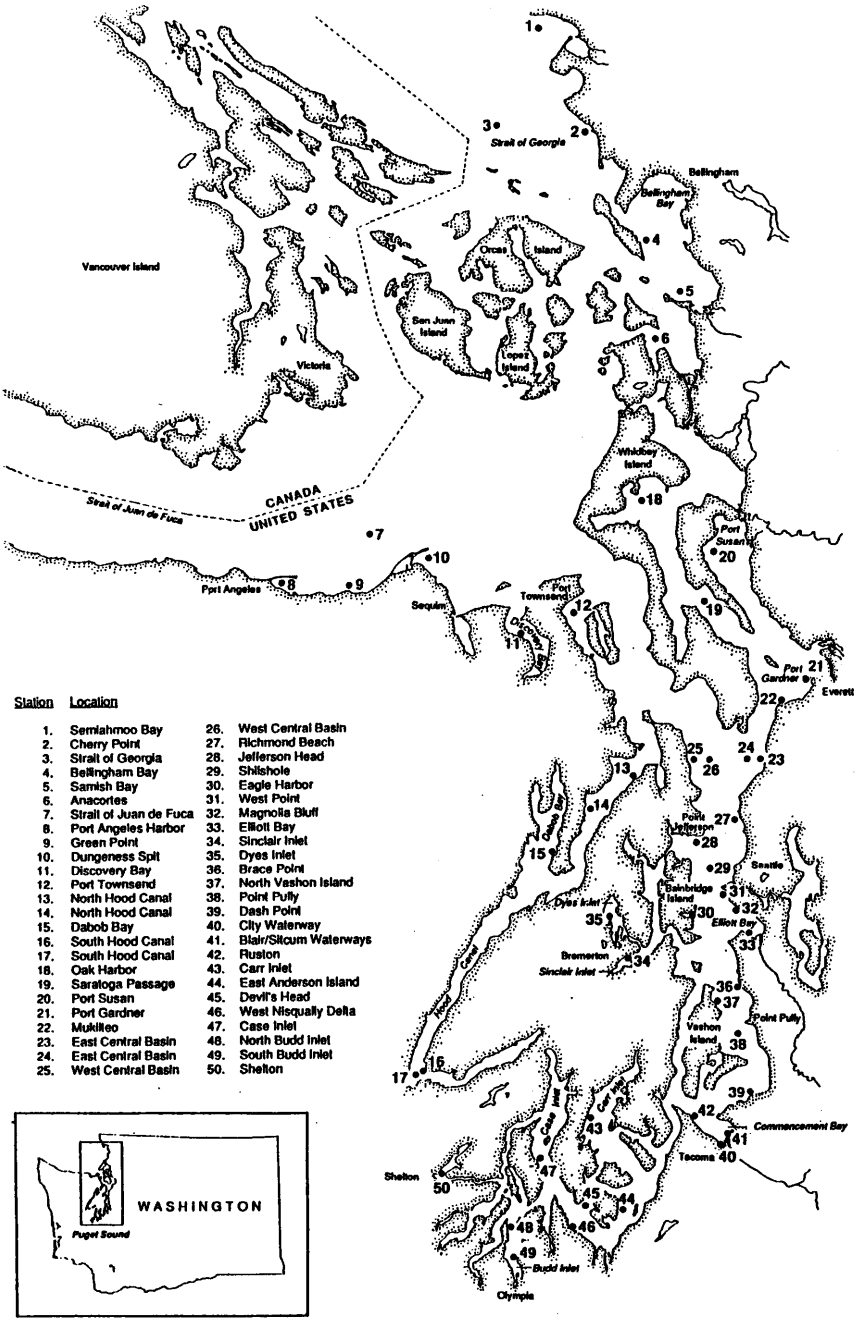

Station	Location		
1.	Semiahmoo Bay	26.	West Central Basin
2.	Cherry Point	27.	Richmond Beach
3.	Strait of Georgia	28.	Jefferson Head
4.	Bellingham Bay	29.	Shilshole
5.	Samish Bay	30.	Eagle Harbor
6.	Anacortes	31.	West Point
7.	Strait of Juan de Fuca	32.	Magnolia Bluff
8.	Port Angeles Harbor	33.	Elliott Bay
9.	Green Point	34.	Sinclair Inlet
10.	Dungeness Spit	35.	Dyes Inlet
11.	Discovery Bay	36.	Brace Point
12.	Port Townsend	37.	North Vashon Island
13.	North Hood Canal	38.	Point Pully
14.	North Hood Canal	39.	Dash Point
15.	Dabob Bay	40.	City Waterway
16.	South Hood Canal	41.	Blair/Sitcum Waterways
17.	South Hood Canal	42.	Ruston
18.	Oak Harbor	43.	Carr Inlet
19.	Saratoga Passage	44.	East Anderson Island
20.	Port Susan	45.	Devil's Head
21.	Port Gardner	46.	West Nisqually Delta
22.	Mukilteo	47.	Case Inlet
23.	East Central Basin	48.	North Budd Inlet
24.	East Central Basin	49.	South Budd Inlet
25.	West Central Basin	50.	Shelton

Figure 1.
LOCATIONS OF SAMPLING STATIONS FOR THE 1989 MARINE SEDIMENT MONITORING TASK.

decontamination procedures and sample collection procedures were in compliance with the Puget Sound Estuary Program Protocols (PSEP, 1986a, 1986b, with revisions). Detailed methods are presented in Tetra Tech (1990).

Laboratory Analyses

At each of the 50 stations the upper 2 cm of sediment were analyzed for 23 metals, 89 semivolatile organics, 24 pesticides/PCB's and conventional variables (e.g., grain size, total organic carbon, total sulfides). Additionally, 37 volatile organic compounds were analyzed for at 10 stations. Analytical methods followed the EPA Contract Laboratory Program (CLP) protocols with modifications recommended in the Puget Sound Protocols to obtain lower detection limits (US EPA, 1988a, 1988b; PSEP, 1986a, 1986b). Sediment toxicity was assessed using the amphipod and Microtox (saline extract) bioassay tests. Five replicate samples of benthic infauna were collected at each station. Due to funding constraints, only three of the five samples were analyzed. Bioassay and benthic infauna laboratory methods followed PSEP (1987) and are detailed in Tetra Tech (1990).

RESULTS

Sediment Chemistry

Metals — Metals concentrations in sediments located away from known contaminant sources were generally low (Table 1), especially relative to concentrations found adjacent to sources in urban embayments. The highest concentrations of arsenic, copper, lead, mercury, silver, and zinc were found at Station 34 in Sinclair Inlet. The highest concentrations of cadmium were found at Station 49 in Budd Inlet, and the highest concentrations of chromium and nickel were found in Port Susan at Station 20. The high concentrations of chromium and nickel in Port Susan were similar to enrichments in the entire Whidbey Basin, which suggests that the Stillaguamish River may be the common source. Three metals that are associated with urban contamination are copper, lead, and zinc. The summed concentration of these metals was greatest at Stations 17, 24, 34, 35, 38, 48, and 49 (Figure 2).

Organic compounds — Most of the organic compounds analyzed for were undetected at very low parts per billion detection limits. Of the 15 acid extractable compounds, only phenol and pentachlorophenol were detected above quantitation limits. The greatest concentration of phenol was found at Station 19 in Saratoga Passage, and the greatest concentration of pentachlorophenol was found at Station 38 in East Passage (Table 1). The only base extractable compound detected was 9(H)-carbazole. It was found at a concentration of 110 ug/kg at Station 40 at the mouth of City Waterway and at Station 26 in the west central Whidbey Basin.

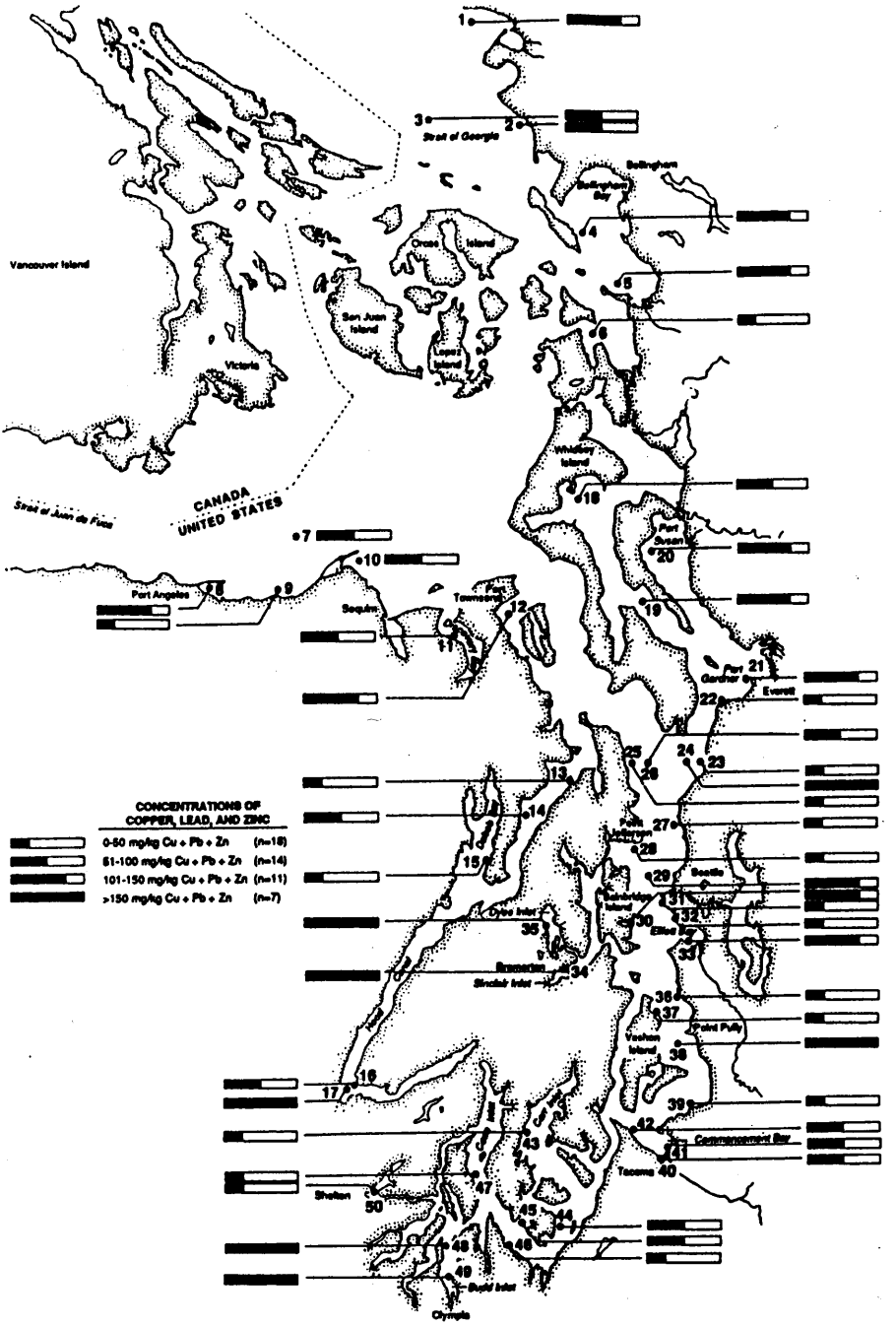

Figure 2.
SUMMED CONCENTRATIONS OF COPPER, LEAD, AND ZINC IN PUGET SOUND SEDIMENTS.

The 34 detected neutral extractable compounds were predominantly low and high molecular weight polycyclic aromatic hydrogens (LPAH and HPAH) and sterols (cholesterol and beta-coprostanol). The distribution of HPAH and LPAH were very similar. The greatest concentrations occurred in the urban embayments, including Stations 40 (City Waterway), 30 (Eagle Harbor), 35 (Dyes Inlet), 34 (Sinclair Inlet), 33 (Inner Elliott Bay) and 8 (Port Angeles) (Figures 3A and 3B).

Table 1.
***CONCENTRATIONS OF SELECTED METALS AND ORGANIC COMPOUNDS** found at stations in the 1989 PSAMP sediment survey. Concentrations are in mg/kg dry wt. for metals and ug/kg dry wt. for organic compounds.*

Compound	Mean (N=50)	Range (N=65)[1]	Frequency of Detection (percent; N=50)	Station with Highest Concentration
Arsenic	4.9	0.74-11.5	100	34 Sinclair Inlet
Copper	23.6	2.7-129	100	34 Sinclair Inlet
Cadmium	0.26	<0.037-1.80	66	49 Budd Inlet
Chromium	29.0	10.8-104	100	20 Port Susan
Lead	14.3	2.2-94.4	100	34 Sinclair Inlet
Mercury	0.13	<0.043-0.86[2]	24	34 Sinclair Inlet
Nickel	27.8	7.9-113	100	20 Port Susan
Silver	0.18	<0.034-1.9[2]	62	34 Sinclair Inlet
Zinc	52.7	14.7-173	100	34 Sinclair Inlet
Phenol	27	7-520[2]	32	19 Saratoga Passage
Pentachlorophenol	0.06	10-<340*	2	38 East Passage
9(H)-Carbazole	12	<8-110	6	26 W Cent. Basin
Naphthalene	9	2-54	34	40 City Waterway
2-Methylnaphthalene	8.7	3-<68	26	38 East Passage
"	45		40	City Waterway
LPAH	160	24-3290	76	40 City Waterway
HPAH	602	36-11540	88	40 City Waterway
beta-Coprostanol	253	<17-4700	80	41 Blair/Sitcum WW
p,p'- DDD	0.052	0.6-2.6	2	33 Inner Elliott Bay
alpha-Chlordane	0.018	<0.2-0.9	2	33 Inner Elliott Bay
Aroclor 1254	12	4.0-49	24	34 Sinclair Inlet
Methylene chloride	4.32	<0.63-52	40	38 East Passage
Acetone	11.1	<0.10-69	40	38 East Passage
Total xylene	0.18	<0.083-0.320	90	38 East Passage

[1] Range includes results of individual field triplicate analyses.
[2] The maximum concentration exceeded the lowest apparent effects threshold (LAET) value.

Data are from Tetra Tech, Inc. 1990.

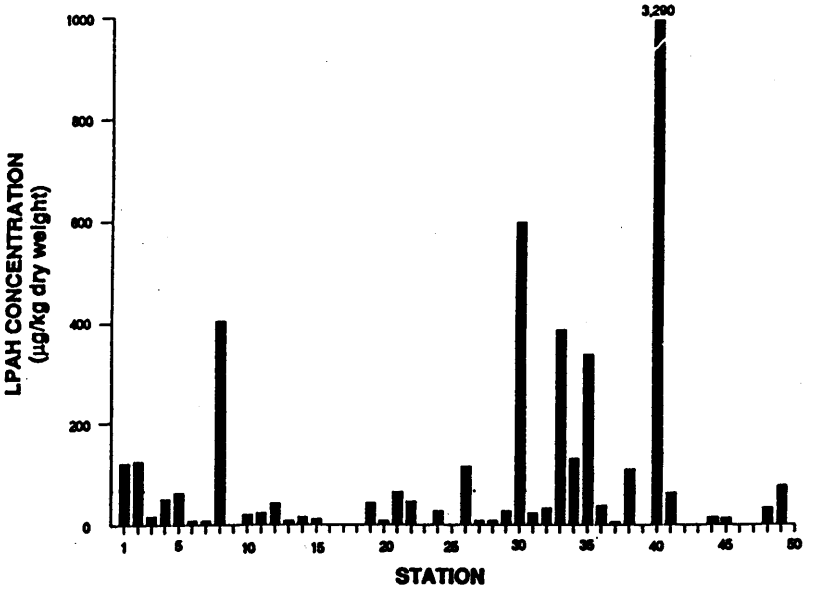

Figure 3A.
CONCENTRATIONS OF LPAH AT SEDIMENT SAMPLING STATIONS.

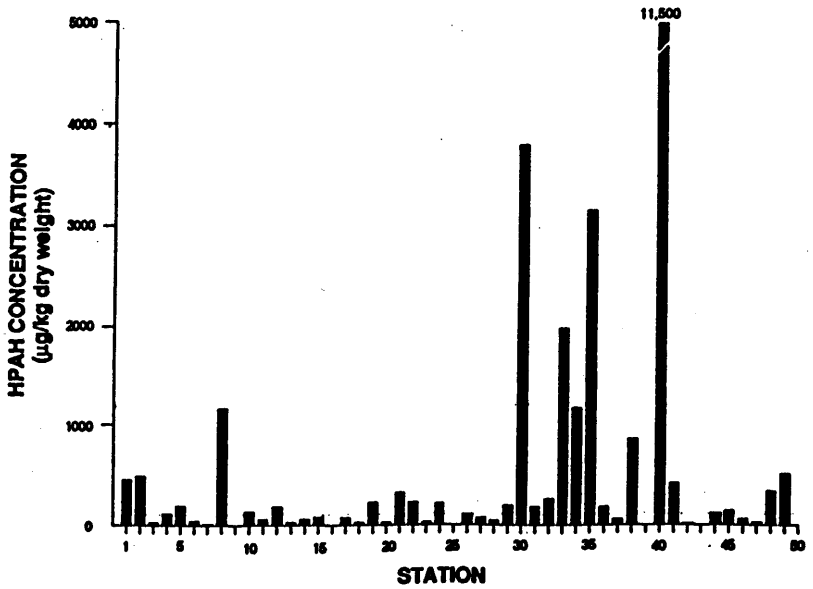

Figure 3B.
CONCENTRATIONS OF HPAH AT SEDIMENT SAMPLING STATIONS.

Beta-coprostanol is a fecal sterol produced by the bacterial breakdown of cholesterol in the digestive systems of ruminants and humans. It can be present in municipal wastewater effluent, combined sewer overflows, and nonpoint source runoff. Although it is not a toxic contaminant, its presence can be used as an indicator of anthropogenic input. As shown in Table 1, the concentration ranged from <17 to 4700 ug/kg DW. The highest concentrations were found in Commencement Bay at Stations 40 and 41, followed by Stations 38 (East Passage), 34 (Sinclair Inlet), and 48 and 49 in Budd Inlet (Figure 4).

The pesticides p,p' DDD and alpha-Chlordane were found at very low concentrations in Inner Elliott Bay at Station 33.

Polychlorinated biphenyls (PCBs) were detected at 24 percent of the stations. Archlor 1254 was the only isomer found. The station with the greatest concentration was in Sinclair Inlet.

Thirty-seven volatile organic compounds were analyzed for at 10 stations, and 18 were detected above quantitation limits. In this study special effort was taken by the analytical laboratory to achieve low quantitation levels for these compounds to determine their ambient or background concentrations. The highest concentrations were found at Stations 29 (Central Basin) and 38 (East Passage). Both stations were classified as deep-depositional stations and appear to be moderately impacted by urban activity.

Sediment Toxicity

The saline extract Microtox bioassay showed no toxicity at any station. While there were fluctuations in luminescence, these fluctuations appeared to be random and not a result of chemical contamination.

The amphipod (*Rhepoxynius abronius*) bioassay also indicated there was little toxicity at the PSAMP stations. At nine stations the sediments could be considered marginally or clearly toxic (≥12.5% mortality), based on the work of Mearns et al. (1986). The data from these nine stations were plotted using the DeWitt et al. (1988) model which was developed to separate particle size effects from toxic effects. This analysis indicated that amphipod mortalities at only one station (Station 35, Dyes Inlet) could be attributed to non-particle size effects. It should be noted that the DeWitt model allows for accepting relatively high mortality in fine grain sediments as "no hit." This approach does not imply that sediments whose contamination falls within the predicted range are uncontaminated.

Benthic Community Structure

A total of 69,962 individuals belonging to 598 taxa were identified at the 50 stations (three field replicates per station). Mean total abundance at stations

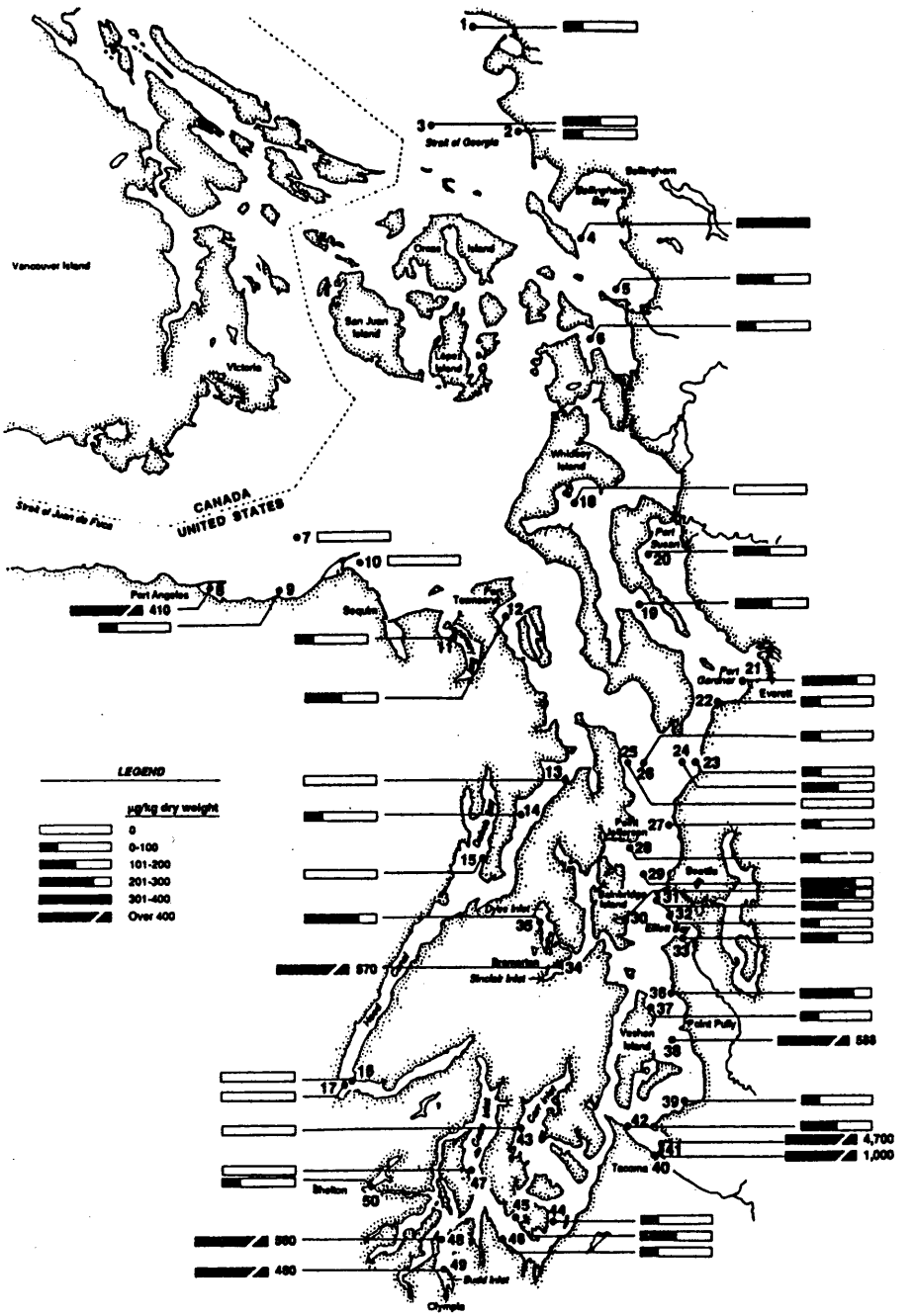

Figure 4.
CONCENTRATIONS OF BETA-COPROSTANOL IN PUGET SOUND SEDIMENTS.

in Puget Sound ranged from 46.7 individuals/0.1 m^2 at Saratoga Passage (Station 19) to 2040.3 individuals/0.1 m^2 at the mouth of the Blair-Sitcum Waterways in Commencement Bay (Station 41). The mean number of taxa ranged from 21.7 taxa/0.1 m^2 at Station 19 to 98.7 taxa /0.1 m^2 at Station 37 (north Vashon Island).

Eighty-seven taxa were numerically dominant (i.e., one of the five most abundant taxa) at one or more stations. Ninety percent of these taxa were dominant at fewer than five stations, which is a further indication of the variety of benthic communities sampled. The ostracod *Euphilomedes carcharodonta* was a dominant taxon at nineteen stations located at water depths less than 52 meters and with sediments containing less than 70 percent fines. The second most frequently dominant taxon was the polychaete *Prionispio steenstrupi.* It was numerically dominant at 14 stations, located in shallow to deep water with sediments containing less than 50 percent fines.

The importance of water depth and particle size in structuring benthic communities was evaluated using a Pearson test of correlation that included mean values for sediment and benthic variables from all 50 stations. Number of taxa and total abundance were both inversely correlated with percent fines ($r = -0.84$ and -0.81, respectively) and total organic carbon content ($r = -0.50$ and -0.74, respectively). These results indicate that the number of taxa and benthic abundance are lower in fine-grained, organically-rich sediments than in coarse sediments. Water depth and both sediment and benthic variables were not highly correlated because a variety of sediment grain sizes were found at all water levels.

Classification analysis using the Bray-Curtis similarity index was used to identify similar stations based on the composition of benthic infauna. All taxa present with an abundance greater than two at a station were included in the total taxa cluster analysis. Three major groups and two outlier stations were defined at a similarity of 20 percent. Within the three major groups, nine subgroups and one subgroup outlier were identified. Characteristics of each cluster group are shown in Table 2, along with variables responsible for defining the subgroups.

Stations within Groups A, B, and C were similar to one another based on sediment particle size, water depth, and geographic area. Mean percent fines was 21.8 percent in Group A and 80.4 percent in Group B. All but one station in Group A were located at water depths less than 25 meters, while the mean water depth at Group B stations was 71.6 meters. Although both grain size and water depth varied between Groups A and B, they were not significantly different ($P<0.05$). Group C comprised Station 9 (Strait of Juan de Fuca) and Station 7 (Green Pt. in the Strait of Juan de Fuca). Although the water depth at Station 7 was substantially greater than at Station 9, the percent fines were

Table 2.
CHARACTERISTICS OF STATION GROUPS AS DEFINED BY CLUSTER ANALYSIS.
Values presented are means. Numbers in parentheses are standard deviations.

GROUP	STATION		DEPTH (m)	% FINES	RICHNESS	ABUNDANCE	DOMINANT TAXA
	Magnolia Bluff	32					
	North Vashon Island	37					
	Richmond Beach	27					
	West Point	31					
A1	Jefferson Head	28	19.4	7.3	75.2	502.1	Euphilomedes carcharodonda
	East Andserson Island	44	(2.5)	(6.6)	(20.8)	(131.5)	Phyllochaetopterus prolifica
	Carr Inlet	43					
	Brace Point	36					
	Dash Point	39					
A2	Dungensis Spit	10	20	30.7	79.0	813.5	Phyllochaetopterus prolifica
	Discovery Bay	11	(0)	(9.2)	(15.1)	(195.4)	
	Dabob Bay	15	13.5	5.4	54.2	746.9	Mysella tumida
A3	South Hood Canal	16	(9.2)	(2.3)	(6.8)	(618.1)	Psephedia lordi
	North Hood Canal	13					
A4	Anacortes	6	20	7.3	71.7	387.8	Psephedia lordi
	Shelton	50	(0)	(3.0)	(13.2)	(166.6)	Axinopsida serricata
	Port Angeles Harbor	8					
	Port Susan	20					
	North Hood Canal	14					
A5	West Central Basin	26	51.1	49.2	52.0	682.5	Axinopsida serricata
	Elliott Bay	33	(80.4)	(27.6)	(12.6)	(595.3)	Tharyx multifilis
	City Waterway	40					Euphilomedes carcharodonta
	Eagle Harbor	30					
	Port Gardner	21					
	Blair/Sitcum Waterway	41					
	Oak Harbor	18					
	East Central Basin	23	20.2	2.7	45.8	363.4	Euphilomedes carcharodonta
A6	West Central Basin	25	(0.3)	(1.3)	(10.3)	(97.7)	Psephedia lordi
	Mulkiteo	22					
	East Central Basin	24					
B1	East Passage	38	162.1	89.0	30.8	130.4	Axinopsida serricata
	Shilshole	29	(56.2)	(4.8)	(9.0)	(39.5)	Euphilomedes producta
	South Hood Canal	17					
	Sinclair Inlet	34					
	Dyes Inlet	35					
	Semiahmoo Bay	1					
B2	Samish Bay	5	18.3	84.7	43.4	406.1	Eudorella pacifica
	Port Townsend	12	(5.4)	(16.3)	(10.5)	(213.6)	Euphilomedes producta
	Cherry Point	2					
	Bellingham Bay	4					
	North Budd Inlet	48	26.6	74.9	33.9	239.2	Eudorella pacifica
B3	South Budd Inlet	49	(24.0)	(17.3)	(12.9)	(83.7)	Pinnixa spp.
	Devil's Head	45					
OUTLIER	Strait of Georgia	3	217.7	32.6	27 (9.5)	254 (166.2)	Prionospio steenstrupi
C	Strait of Juan de Fuca	7	77.0	3.7	55.7	445.5	Ampelisca spp.
	Green Point	9	(79.0)	(3.4)	(15.4)	(79.9)	Mediomastus californiensis
OUTLIER	Ruston	42	39	3.2	31.3 (6.4)	89.0 (7.2)	Prionospio steenstrupi
	Saratoga Passage	19	121	81.3	21.7 (1.5)	46.7 (4.5)	Olivella baetica

similar (mean = 3.7 percent). Because water depth and percent fines at these stations were similar to many stations in Groups A and B, Group C stations appear unique because of the degree of wave exposure and water current actions that influence community composition.

DISCUSSION

The question that arose numerous times during the development of the marine sediment task was "How dirty are the sediments in Puget Sound?" The extent to which anthropogenic pollution has degraded sediment quality throughout Puget Sound is slowly coming into focus. Surveys sponsored by federal and state agencies have documented degraded sediment quality in many urban embayments. The 1989 PSAMP survey provides some of the first synoptic data for nonurban areas of the Sound. Because the stations were positioned away from contaminant sources, we now have data with which to assess how dirty the sediments are in the major portion of Puget Sound.

Sediment chemical concentrations in shallow water areas away from sources were generally low or less than could be detected. However, in urban embayments those chemicals were usually detected at higher concentrations. Data presented in Table 1 show that the highest concentrations of chemical contaminants were consistently found in Sinclair Inlet, the mouth of City Waterway, Inner Elliott Bay and in Budd Inlet. These results are consistent with other surveys.

Of potential concern are the elevated concentrations of organic compounds found at the deep station in East Passage. Other stations located in deep water and not near sources of contamination also contained measurable concentrations of toxic chemicals. Some examples include beta-coprostanol, methylene chloride, and acetone at Station 3 in the Strait of Georgia; beta-coprostanol and LPAH at Station 26 in Whidbey Basin; and all of the above at Station 29 off Seattle. At Station 19 in Saratoga Passage, which is not near any known contaminant sources, the concentration of phenol exceeded the lowest apparent effects threshold (LAET). In addition, beta-coprostanol, methylene chloride, acetone, and total xylene were found there. The accumulation of toxic contaminants at these deep stations suggests that some contaminant-bound particulates that originate in urban embayments may be settling out of the water column in the deep basins of Puget Sound.

The station in Dyes Inlet was the only one to exhibit significant sediment toxicity. It appears that sediments sampled during the 1989 survey in areas located away from potential sources are not toxic.

Despite the presence of chemical contaminants at many nonurban stations, most of the benthic invertebrate communities were healthy. This was the

case even at stations where the concentration of a chemical exceeded its LAET value. The abundance and species richness of the benthic communities varied greatly throughout the Sound, primarily in relation to sediment particle size.

With the exception of the urban embayments, the sediments in Puget Sound appear to be relatively clean and non-toxic. Sediments in the deep basins of Puget Sound need continued monitoring because they have accumulated chemical contaminants despite their being located away from contaminant sources.

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WHAT CONTAMINANTS ARE IN OUR FISH?

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INTRODUCTION

Puget Sound offers excellent commercial and recreational fishing opportunities, but recent and projected urban growth raises concerns about increased water pollution and the resulting impacts on fish. The Washington Department of Fisheries (WDF) has initiated a study to monitor the accumulation of contaminants in selected recreational and commercial fishes from Puget Sound. This study is one component of the Puget Sound Ambient Monitoring Program (PSAMP), a multi-agency effort to assess the environmental health of Puget Sound. Unlike other Puget Sound studies, this study is a long-term project that collects information on an annual or biannual basis from a wide geographic area, involves six species of fish, and monitors integrated contaminant loading from multiple rather than point sources. Additionally, these data can be compared with other PSAMP data on contaminant levels in nearby sediment stations to determine if contaminants in sediments bioaccumulate in local fish communities.

The specific objectives of this study are to: document current tissue contaminant levels, determine frequencies of pathological disorders in English sole, track changes in tissue contaminant levels and pathological disorders from year to year, and assess the impact of contamination on fish health. The first cycle of sampling has been completed, and an overview of the results is presented here. A complete review of the first cycle's results is presented in O'Neill and Schmitt (in prep). The Washington Department of Health, Office of Toxic Substances, is currently reviewing our results to estimate any potential human health effects associated with consuming these Puget Sound fishes.

MATERIALS AND METHODS

Species and Site Selection

Fish with different diets may experience various levels of exposure to contaminants present in the sediments and water. For example, benthic species, such as English sole (*Parophrys vetulus*), live and feed near the sediments and are likely to be exposed to higher contaminant levels than species like Pacific herring (*Clupea harengus*) that live and feed in the pelagic zone. Ideally, the

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fish species selected for monitoring should include benthic and pelagic feeders, as well as demersal species that live near the bottom. Further, to assess human health risks, the species chosen should be common in commercial and recreational catches in Puget Sound. As a result, English sole, quillback and copper rockfish (*Sebastes maliger* and *S. caurinus*), Pacific cod (*Gadus macrocephalus*), and coho and chinook salmon (*Oncorhynchus kisutch* and *O. tshawytscha*) were selected for study. These species were collected in four surveys by the methods outlined in the Fish Monitoring Task Implementation Plan (Stern, 1989).

Flatfish Survey — English sole, a representative flatfish, is an excellent target species for bioaccumulation and pathological studies. They are commonly caught commercially and are widely distributed, yet movements of particular populations are restricted to localized areas (Day, 1976). They represent a "worst case" indicator of contaminants in fish because of their close association with the bottom sediments and their consumption of benthic invertebrates. A 400-mesh eastern trawl was used to collect English sole from "urban" bays (Elliott Bay, Sinclair Inlet and Commencement Bay), "near-urban" areas (outer Port Townsend, outer Bellingham Bay, Port Gardner, and outer Budd Inlet), and "non-urban" areas (Strait of Georgia, Discovery Bay, and Hood Canal) in May, 1989 (Figure 1).

Cod Survey — Pacific cod are demersal and feed on fish and invertebrates living on or near the bottom. They are a popular recreational and commercial species. Cod migrate over large areas within Puget Sound but seldom migrate to the open ocean. Consequently, contaminants found in cod from a particular location reflect background contaminant levels over a broad area rather than site-specific contaminant problems. A commercial bottom trawl was used to collect cod from Admiralty Inlet (Figure 1) in March, 1990.

Rockfish Survey — Quillback and copper rockfish are also demersal fishes that feed on fish and invertebrates living on or near rocky bottom habitats. They are important in the recreational catch. These rockfish are predominantly nonmigratory (Matthews, 1990), and contaminants found in their muscle tissue probably reflect site-specific contaminant problems. Because these rockfish may live for 30 years or longer and spend much of their lives in one area, they may bioaccumulate higher levels of contaminants found at very low levels in bottom sediments or prey than shorter-lived fish. Rockfish were collected from two sites in October 1990 by SCUBA divers with spear guns or by hook and line. Quillback rockfish were collected at Day Island (southern Puget Sound), and copper rockfish were collected at Blakely Rock (Figure 1).

Salmon Survey — "Resident" chinook salmon and coho salmon spend most of their marine lives in Puget Sound rather than the open ocean. Chinook and

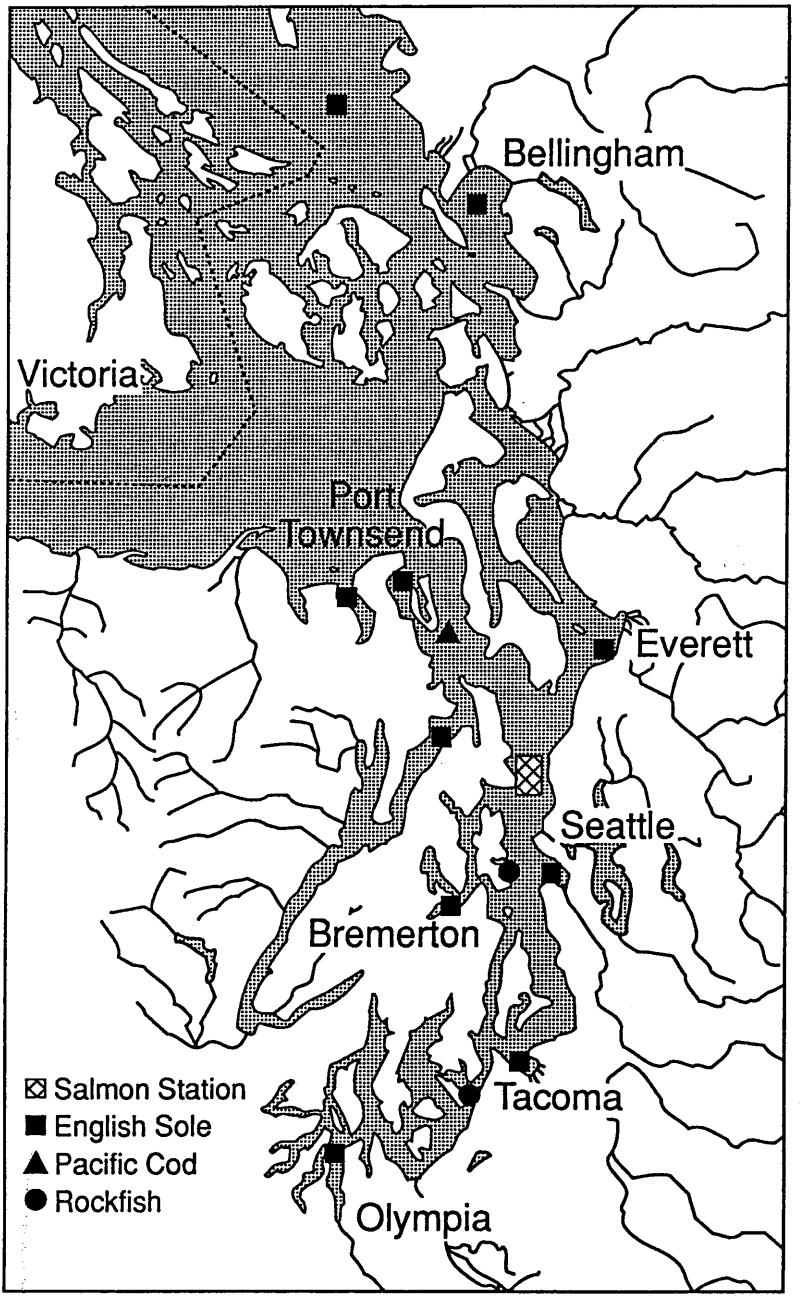

Figure 1.
1989 PSAMP FISH SAMPLING SITES.

coho are important components of the commercial and recreational catch. These pelagic fish generally inhabit the upper water column consuming mainly fish, euphausids, juvenile crab and zooplankton (Beacham, 1986). Like cod, contaminants found in resident salmon from any one location reflect contaminant levels over a wide geographic area, as salmon migrate over large areas of Puget Sound. Coho and chinook samples were collected with a commercial purse seine from central Puget Sound (Figure 1) in the late spring of 1990.

General Sampling Methodology

Collected fish were weighed and measured (fork length for Pacific salmon and total length for all other species), and gender was determined. Gill interoperculum, otoliths and scales were collected for age determination of English sole, rockfish, and Pacific salmon, respectively. Pacific cod ages were estimated from fish length. The edible muscle tissue was then removed for chemical analysis. For each species, muscle tissue from five fish was combined to make one composite sample. Three composite samples per site were collected for English sole. Six composites per site were collected for all other fish species unless insufficient numbers of fish were captured.

Muscle tissue samples were frozen until they were analyzed for the presence of trace metals (arsenic, mercury, lead and copper), polychlorinated biphenyls (PCBs), and pesticides and other extractable organic compounds that are known to be carcinogenic and/or to bioaccumulate (e.g., chlorinated hydrocarbons and phenols). Chemical analyses were conducted according to the Puget Sound Estuary Program's recommended guidelines for measuring organic and inorganic compounds in sediment and tissue samples (PSEP, 1989a, 1989b),except as noted in O'Neill and Schmitt (in prep).

Additionally, sections of liver were removed from 60 English sole (≥20 cm) from each flatfish site. The liver sections were preserved in 10% neutral buffered formalin, embedded in paraffin, sectioned with a rotary microtome, mounted on slides, and stained with hematoxylin and eosin dyes. A fish pathologist examined the samples microscopically to detect tumors or other liver abnormalities. All sampling was conducted according to the PSEP recommended protocols for fish pathology studies (1987).

RESULTS

Contaminant Levels in Fish Tissue

Size and age of fishes sampled—English sole ranged in size from 20 to 44 cm (total length) and were two to 14 years old. Mean ages of English sole used in composite muscle tissue samples varied among sites; fish collected from

Sinclair Inlet, Elliott Bay, Commencement Bay and Hood Canal were older (mean ages = 9.1, 7.7, 6.2, and 6.2 years, respectively) than fish collected from the Strait of Georgia, Port Gardner, Port Townsend, Budd Inlet, Discovery Bay and Bellingham Bay (mean ages = 5.5, 4.9, 4.5, 3.3, 3.2 and 2.7 years, respectively). Rockfish ranged in size from 21 to 43 cm (total length). Rockfish varied in age (two to 16 years) and the age compositions in the composites were roughly equivalent among composites and sites. The mean ages of quillback and copper rockfish were seven and six years, respectively. The sizes of cod ranged from 41 to 70 cm (total length), approximately corresponding to three- to five-year-old fish. All coho were in their third year (fork lengths: 35 to 47 cm). The chinook salmon varied in age from two to three years and their fork lengths ranged from 33 to 49 cm.

Trace metals — With the exception of arsenic, the concentrations of trace metals in all fish species were low (Table 1). Arsenic was detected in all English sole samples at concentrations ranging from 1.80 to 11.00 ppm. Mean concentrations of arsenic were lower in Pacific cod (4.92 ppm), considerably lower in rockfish (0.67 ppm), and not detected in the salmon samples. In previous studies, chemical analysis for arsenic has not routinely been conducted for salmon, so we do not know if arsenic is usually present.

Copper was detected at low levels in all fish samples and mean concentrations were similar among fish species (English sole, 0.24 ppm; quillback rockfish, 0.20 ppm; copper rockfish, 0.22 ppm; Pacific cod, 0.23 ppm; coho salmon, 0.25 ppm; and chinook salmon, 0.28 ppm). English sole from all 10 sites contained similar copper concentrations.

Lead was only detected in 39% of the samples. When detected, it was present at low levels (<0.11 ppm). Lead concentrations in all three English sole samples from Sinclair Inlet were consistently higher (mean = 0.07 ppm) than those of the English sole samples from other sites (mean = 0.05 ppm) and for all other fish species (means 0.02 to 0.03 ppm).

Mercury was detected at low concentrations in all English sole samples; however, in some cases the data were rejected because of poor laboratory quality. English sole sampled from inner "urban" bays (Elliott Bay, Sinclair Inlet and Commencement Bay) had mean mercury concentrations of 0.06 to 0.07 ppm. Mercury concentrations in coho and chinook salmon were similar to those found in English sole from "urban" bays, whereas rockfish and Pacific cod had considerably higher mean concentrations (0.10 and 0.13 ppm, respectively).

Trace organics — Few toxic organic compounds were detected in the fish species sampled in the first cycle of this study (Table 2). PCBs were detected at low levels in all English sole samples from the three "urban" bay sites and at

Table 1.
***MEAN CONCENTRATIONS OF TRACE METALS (PPM, WET WEIGHT)** in fish muscle tissue collected from Puget Sound during the first PSAMP monitoring cycle. Means are calculated based on 3 composites for English sole, 6 composites for rockfish species and coho salmon, 5 composites for Pacific cod, and 4 composites for chinook salmon.*

	Concentration of Trace Metal			
Site	Arsenic	Copper	Lead	Mercury
English sole				
St. of Georgia	3.43	0.23	0.05**	0.06^
Bellingham Bay	3.80	0.23	ND(0.04)	– ^^^
Discovery Bay	6.67	0.22	0.07*	– ^^^
Port Townsend	5.03	0.19	0.06*	– ^^^
Port Gardner	4.53	0.22	0.05*	0.05^^
Elliott Bay	6.40	0.22	0.05*	0.07
Sinclair Inlet	8.67	0.27	0.07	0.07
Commencement Bay	5.67	0.23	ND (0.04)	0.06
Budd Inlet	5.90	0.36	0.04**	– ^^^
Hood Canal	4.73	0.21	ND (0.04)	0.06
Rockfish				
Blakely Rock	0.89	0.22^^	ND (0.03)	0.10
Day Island	0.45	0.20	ND (0.03)	0.10
Pacific Cod				
Admiralty Inlet	4.92	0.23^^^	0.02***	0.13
Pacific Salmon				
Central (coho)	ND (0.10)	0.25	0.02*	0.05
Puget (chinook) Sound	ND (0.09)	0.28	0.03*	0.07

* Metal was not detected in 1 composite; detection limit used to calculate mean.
** Metal was not detected in 2 composites; detection limit used to calculate mean.
***Metal was not detected in 4 composites; detection limit used to calculate mean.
ND = Not detected in any of the composite samples at mean detection limit shown.
^ = data from 1 composite was rejected and not used to calculate mean.
^^ = data from 2 composites were rejected and not used to calculate mean.
^^^= data from 3 composites were rejected and not used to calculate mean.

one of the "near-urban" sites, but were not detected in any of the "non-urban" sites. The highest total PCBs (calculated as Arochlor 1254 + 1260) were found in English sole from Sinclair Inlet (102.33 ppb). PCBs were detected at low concentrations in only one of the six quillback rockfish composite samples and were not detected in the copper rockfish. We did not detect PCBs in Pacific cod or salmon.

Benzyl alcohol was consistently found in English sole samples from sites within the central and southern Puget Sound basins, but it was detected in only a few of the samples from northern sites (Table 2). Benzyl alcohol was not detected in any of the copper rockfish, Pacific cod and Pacific salmon compos-

Table 2.
***MEAN CONCENTRATIONS OF SELECTED TRACE ORGANICS (PPB, WET WEIGHT) IN FISH MUSCLE TISSUE** collected from Puget Sound during the first PSAMP monitoring cycle. Means are calculated on 3 composites for English sole, 6 composites for rockfish species and coho salmon, 5 composites for Pacific cod, and 4 composites for chinook salmon.*

	Concentration of Trace Organics			
Site	PCB Arochlors 1254/1260	4,4-DDE	Benzyl Alcohol	Phenanthrene
English sole				
St. of Georgia	ND / ND (8.40)	ND (1.67)	24.10**	ND (7.20)
Bellingham Bay	ND / ND (12.90)	ND (2.58)	ND (41.67)	ND (8.73)
Discovery Bay	ND / ND (12.33)	ND (2.07)	30.05**	ND(10.27)
Port Townsend	ND / ND (9.10)	ND (1.28)	30.86	ND (7.87)
Port Gardner	13.67 / 9.03	0.77*	39.06	ND (5.60)
Elliott Bay	24.67 / 14.33	1.13	37.72	ND (5.90)
Sinclair Inlet	35.33 / 67.00	1.37*	53.00	ND (5.60)
Commencement Bay	26.33 / 16.40**	1.63*	55.36	ND (5.53)
Budd Inlet	ND / ND (7.07)	ND (1.40)	86.11	ND (5.93)
Hood Canal	ND / ND (6.67)	1.04**	40.26*	ND (5.60)
Rockfish				
Blakely Rock	ND / ND (3.30)	0.50*	ND (11.00)	8.73*
Day Island	5.58***/ND(4.42)	0.84**	22.0***	9.08***
Pacific Cod				
Admiralty Inlet	ND (3.30)	ND (0.33)	ND (13.00)	ND(13.00)
Pacific Salmon				
Central (coho)	ND / ND (3.30)	0.57**	ND (13.00)	ND(13.00)
Puget (chinook) Sound	ND / ND (3.30)	0.60	ND (13.00)	ND(13.00)

* Chemical was not detected in 1 composite; detection limit used to calculate mean.
**Chemical was not detected in 2 composites; detection limits used to calculate mean.
***Chemical was not detected in 5 composites; detection limits used to calculate mean.
ND = Not detected in any of the composite samples at mean detection limit shown.

ite samples, but was detected in one of the six quillback rockfish composite samples.

No organochlorine pesticides were detected in any of the fish muscle tissue samples; however, 4,4-DDE, a breakdown product of the organochlorine pesticide DDT, was detected at low levels (<2.00 ppb) in most of the rockfish and salmon samples, and in English sole samples from "urban" and "near-urban" sites. 4,4-DDE was not detected in any of the Pacific cod samples. Low levels (<10.00 ppb) of phenanthrene, a polyaromatic hydrocarbon (PAH), were detected in many of the quillback and copper rockfish but not in the other fish species.

Prevalence of Neoplastic and Related Lesions in English Sole

Size and age of fish sampled — English sole ranged in size from 20 to 45 cm (total length) and were 2 to 16 years old. Mean ages of English sole used for histopathology samples varied among sites. The youngest fish were collected from Bellingham Bay, Budd Inlet, Discovery Bay and Port Townsend (mean ages 2.9 to 4.4 years). Fish of similar ages were collected from Hood Canal, Strait of Georgia and Port Gardner (mean ages = 5.6, 5.2 and 5.1 years, respectively). The oldest fish were collected from Elliott Bay, Sinclair Inlet and Commencement Bay (mean ages = 8.6, 7.6 and 6.0 years, respectively).

Liver histopathology — The overall prevalence of fish affected with liver lesions classified as neoplasms, pre-neoplasms, and degenerative lesions that are associated with neoplasms (megalocytic hepatosis and nuclear pleomorphism) was moderate at "urban sites" (20% at Elliott Bay; 13.3% at Commencement Bay; 5% at Sinclair Inlet), very low in one of the "near-urban" sites (1.7% at Port Gardner), and absent at all other sites.

DISCUSSION

Tissue Chemistry Data: Comparisons with Previous Studies

The first cycle's results indicate that, overall, the edible muscle tissue of most Puget Sound fish contain trace metals but few organic contaminants. Generally, the concentrations of all four metals (arsenic, copper, lead and mercury) are consistent with the ranges of concentrations reported in previous studies of Puget Sound fishes (Romberg et al., 1984; Tetra Tech, 1985; Landolt et al., 1987; PTI, 1990). Arsenic was elevated in most English sole and Pacific cod samples relative to other species. The Puget Sound Naval Station at Bremerton may have contributed to the arsenic levels in Sinclair Inlet (Tetra Tech, 1990); however, natural sources likely contribute, most of the arsenic detected in Puget Sound fishes. Natural sources of arsenic, including oceanic water, rivers, and shoreline erosion contribute over ten times more arsenic to Puget Sound than do anthropogenic sources (Dexter et al., 1981; Landolt et al., 1987). The ASARCO smelter, a former point source for arsenic in central and southern Puget Sound, closed in 1984.

The mean mercury concentrations reported in rockfish and Pacific cod from other Puget Sound studies (Gahler et al., 1982; Landolt et al., 1987) are lower than those we found, whereas similar concentrations of mercury were found in English sole from this study and other studies (Tetra Tech, 1985; Landolt et al., 1987).

PCBs were used extensively as coolants and frequently mixed with oils and greases in electrical transformers. Although the manufacture of PCBs has been banned since 1977, PCBs continue to persist in the environment. Previ-

ous studies have shown that PCBs are present in the sediments in some areas of Puget Sound and are bioaccumulated by many marine organisms. When comparing our results with those of previous studies, we only reviewed similar studies that also measured levels of PCBs in fish muscle tissue (wet weights) on the same species of fish. Although, fish species and tissue types were similar in all of these studies, the methodology used to quantify the PCBs varied among studies and thus the data generated are not totally equivalent. The levels of PCBs found in English sole in our study were similar to the concentrations reported by Landolt et al. (1987); however, English sole sampled in the late 1970s and early 1980s (Malins et al., 1980, 1982) had substantially higher concentrations. Although PCBs were only detected in one of 12 rockfish composite samples, the value was within the ranges reported by Landolt et al. (1987). PCBs were not found in salmon in this study but were detected in previous studies (Malins et al., 1982; Galvin et al., 1984). Landolt et al. (1987) detected low to moderate concentrations of PCBs in Pacific cod sampled from public fishing piers and boat ramps in Puget Sound; however, we did not detect PCBs in the cod we sampled. Other discrepancies between levels of PCBs in Pacific cod and salmon in our results and previous studies may be due to differences in the size of fish analyzed, the location and seasonal variations, or they may reflect actual declines in PCBs.

The levels of 4,4-DDE detected in fish in our study were generally lower than those reported in previous studies (Gahler et al., 1982; Galvin et al., 1984; Landolt et al., 1987). This observation is consistent with results reported by Matta et al. (1986) and Mearns et al. (1988) who showed that organochlorine pesticides and their metabolic breakdown products have decreased in fish from Elliott Bay over time.

Low concentrations of phenanthrene (PAH) were detected in Pacific cod and rockfish sampled by Landolt et al. (1987), but this compound was only detected in rockfish in this study. No other PAHs were detected, but generally, fish do not bioaccumulate PAHs in their muscle tissues (Krahn et al., 1986).

The most surprising organic compound that was detected in English sole was benzyl alcohol, as it has not routinely been reported in Puget Sound studies. Benzyl alcohol is used as a solvent in some cosmetic supplies, as a degreasing agent in rug cleaners and in the photographic development of color film. Benzyl alcohol has also been detected in motor vehicle exhaust and may be released into the atmosphere and deposited in the soil by rain washout.

Tissue Chemistry Data: Comparisons with PSAMP Sediment Data

Tissue chemistry data collected from English sole sampled at 10 sites in Puget Sound can be compared to sediment chemistry data collected at 10 nearby PSAMP sediment sites. Sediment samples were not taken at the rockfish sites, as these sites were located on rocky reefs. Given the migratory nature of

Pacific cod and salmon, it is not appropriate to compare tissue chemistry data with sediment chemistry data collected from specific sites.

Low levels of several heavy metals were present in most of the marine sediments sampled during the first year of the PSAMP sediment monitoring task. Sediment monitoring was conducted by the Washington Department of Ecology (Tetra Tech, 1990). At most sites, high concentrations of metals in sediments did not coincide with high concentrations of metals in the muscle tissue of English sole. Sinclair Inlet was a notable exception; the highest concentrations of arsenic, copper, lead and mercury were found in sediments there. English sole from this site had consistently higher levels of these metals in their tissues than did English sole from other sites. However, English sole from Sinclair Inlet were also considerably older than sole sampled from other sites, possibly explaining the higher levels of metals in the muscle tissue.

PCBs were detected in sediments at five of the 10 English sole sampling sites, and PCBs were detected in fish muscle tissue in four of these five sites. Generally, higher levels of PCBs in sediments are associated with higher levels of these compounds in fish muscle tissue. Arochlor 1254 was found in progressively higher amounts in sediments at Port Gardner, Elliott Bay and Sinclair Inlet (30, 40, and 49 ppb, dry weight). Similarly, progressively higher levels of Arochlors 1254 and 1260 were found in English sole from Port Gardner, Elliott Bay and Sinclair Inlet (23, 39, and 102 ppb, wet weight). The Commencement Bay and Budd Inlet sites were exceptions. Arochlor 1254 and 1260 were present at moderate levels (43 ppb, wet weight) in English sole from Commencement Bay, but were only detected at very low levels in the sediments. Arochlor 1254 and 1260 were not detected in English sole from Budd Inlet but were detected in the sediments (18 ppb, dry weight).

4,4-DDD, the environmental breakdown product of the organochlorine pesticide DDT, was present in the sediments at Elliott Bay, but no other breakdown products (eg., 4,4-DDE) were found at any of the other PSAMP sediment sites. 4,4-DDD was detected in one of the six quillback rockfish composite samples but was not detected in the other fish species. Although not detected in the sediments, low levels of DDE, another breakdown product of DDT, were detected in many of the fish species. Many of the organochlorine pesticides analyzed under PSAMP are no longer manufactured or used by the agriculture industry. These pesticides are probably present in sediments below levels that could be detected but that still can be bioaccumulated by fish.

Benzyl alcohol was not found in any of the sediment samples, yet was often detected in English sole muscle tissue, especially in the southern and central Puget Sound sites. Although benzyl alcohol was not detected in the sediments, toluene was present. Toluene is a volatile organic compound that can be metabolized by fish to form benzyl alcohol (Nishimoto, pers. comm.).

Toluene and similar volatile organic compounds have been observed at low concentrations in pristine forests and marine environments due to natural processes (Farlow, 1977).

Prevalence of Liver Lesions in English Sole

The liver is the organ in fish that is most commonly afflicted with pathological disorders (Malins et al., 1980, 1982). Although the causes of neoplastic liver lesions in feral fish have not definitely been determined, morphologically similar lesions have been induced in laboratory mammals and fishes exposed to toxic chemicals, particularly PAHs (Malins et al., 1984; Myers et al., 1987; Schiewe et al., 1988). The step-wise histogenesis of hepatic neoplasia in vertebrates also suggests that some lesions (megalocytic hepatosis and nuclear pleomorphism) induced in the laboratory are precursors to neoplasms (Myers et al., 1988). Thus, the prevalence of neoplasms, preneoplasms, megalocytic hepatosis and nuclear pleomorphism in English sole may indicate that the fish have been exposed to toxic chemicals. The prevalences of neoplastic and neoplastic-associated liver lesions in our study are comparable to those reported in previous studies (Crecelius et al., 1989; Malins et al., 1984; Pacific Northwest Laboratories, 1986; Tetra Tech, 1985).

Prevalence of Liver Lesions in English Sole vs. Contaminant Levels in Sediments

PSAMP sediment monitoring by the Washington Department of Ecology found that the most common organic contaminants found in sediments were PAHs (Tetra Tech, 1990). PAHs include low molecular weight compounds that are derived from petroleum fuel and oil, as well as high molecular weight compounds that result from the combustion of hydrocarbons. With the exception of phenanthrene, a PAH detected at low levels in many of the rockfish samples, PAHs were not present in the muscle tissue of the fish we sampled. Fish generally breakdown PAHs to metabolites that accumulate in the bile and then are excreted, rather than being accumulated in muscle tissue (Krahn et al., 1986). However, the levels of these metabolites of PAH (called fluorescent aromatic compounds) are positively correlated with prevalence of liver lesions (Myers et al., 1987).

Liver histopathology data on English sole were compared to sediment chemistry data for those sediment sampling sites that overlap with the fish sampling sites. The first cycle of PSAMP monitoring indicated that the frequency of neoplastic and neoplastic-associated liver lesions in English sole was highest in fish caught in Elliott Bay and Commencement Bay, second highest for Sinclair Inlet samples, and third highest for Port Gardner samples. The same ranking of total PAH concentrations was found in sediments from these locations. Fish age may also have influenced the prevalence of these liver

lesions as English sole from Elliott Bay, Sinclair Inlet and Commencement Bay (mean ages = 8.6, 7.6 and 6.0, respectively) were considerably older than fish from other sites. However, within these three sites, mean fish age did not appear to be related to the prevalence of liver lesions.

Prevalence of Liver Lesions in English sole: Impacts on Fish Health

Fish with contaminant induced tumors also show clinical evidence of organ dysfunction (Casillas et al., 1983) indicating their health is being compromised by the presence of the tumors (NMFS' Habitat Conservation Program Briefing Summary, 1990). Thus, particular English sole populations in areas where we found an elevated prevalence of liver lesions (Elliott Bay and Commencement Bay) may be significantly affected. However, we do not have English sole abundance data to detect impacts on populations for these areas. Data from wider geographic areas indicate that English sole populations in central and southern Puget Sound appear to be relatively abundant and stable (Schmitt, 1990).

Human Health Risks Associated with Consuming Puget Sound Fish

WDF is working cooperatively with the Washington State Department of Health to determine if the contaminants detected in Puget Sound fishes pose a health risk to consumers. In particular, the levels of arsenic found in English sole and the levels of mercury found in rockfish and Pacific cod are being investigated.

CONCLUSIONS AND RECOMMENDATIONS

Overall, results from the first cycle of monitoring indicate that in the fish we sampled, few organic contaminants were present and with the exception of arsenic, the levels of trace metals were generally low. When compared with previous Puget Sound studies, the levels of PCBs and pesticides appear to be lower. It is important to remember, however, that we have only completed one cycle, that the scope of our survey was geographically limited, and that we did not sample known contaminant "hot spots".

The detection of benzyl alcohol in English sole, although at low levels, warrants careful scrutiny in future sampling cycles to determine if it is coming from toluene in the sediments. Additionally, we did not test for many toxic chemicals that are known to be present in Puget Sound, including dioxins, alkyl tins and the currently used pesticides. Testing at additional sites and for more toxic compounds will be included in future sampling.

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MICROBIOLOGICAL AND CHEMICAL CONTAMINANTS IN PUGET SOUND SHELLFISH

Clive Pepe and Gary Plews[1]

This paper summarizes the first year of shellfish results from the Puget Sound Ambient Monitoring Program (PSAMP), carried out by the Washington Department of Health (WDOH), Office of Shellfish Programs. More detailed results and discussions are available in the Department of Health's PSAMP Annual Technical Report (WDOH, in prep.).

INTRODUCTION TO PSAMP SHELLFISH MONITORING

The Department of Health, Office of Shellfish Programs, completed a final implementation plan (WDOH, November 89) for PSAMP shellfish sampling in 1989. The plan rationale was to provide baseline and long term data about contaminants and their rate of change in shellfish tissue. Shellfish tissue from 35 beaches were to be analyzed for three parameters: bacteriological levels, chemical concentration of metals and organic compounds, and concentrations of paralytic shellfish toxin (PSP)—a marine biotoxin.

Full funding for the initial biennium (1989-91) plan was not available, resulting in a reduced number of sampling sites. An overview of funded PSAMP shellfish monitoring can be found in Table 1. WDOH staff, and volunteers from Adopt-a-Beach and Chautauqua Northwest, collect samples.

Table 1.
1989-91 FUNDED PSAMP SHELLFISH SAMPLING PLAN INCLUDING PARAMETERS AND PROTOCOL.

Parameter	Sites		Target Species	Frequency of Sampling	Laboratory	Tests (protocol)
	1990	1991				
Bacteriology	10	12	P. staminea (native littleneck)	4/year Commenced November 1989	WDOH Public Health Laboratory	Fecal Coliform Most Probable Number (MPN) (APHA 1970)
Chemical	4	11	P. staminea (native littleneck)	Annual Commenced May 1990	Municipality of Metropolitan Seattle (METRO)	Modified EPA priority pollutant scan and 6 metals (Puget Sound Protocols 1990)
Marine Biotoxin	16	16	Various	Throughout year Commenced November 1989	WDOH Public Health Laboratory	Bioassay PSP toxin in shellfish tissue (APHA 1984)

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PLAN DESIGN

Shellfish were analyzed for three parameters: bacteria, chemicals and marine biotoxins. (See Table 1 for respective parameter tests and protocols.)

Bacteriology and Chemical — The target species was *P. staminea* (native littleneck); if the target species was in low abundance, *T. japonica* (manila littleneck) or *S. giganteus* (butter clam) were sampled. Target species selection was based upon the fact that native littlenecks and butter clams are most frequently harvested by Washington State recreational diggers (Price and Ladd, 1978). Table 2 lists the ten bacteriological sites and species tested for fecal coliform concentrations.

Four sites were analyzed for chemicals in native littlenecks during May 1990. The small number of 1990 sites was to clarify analytical and interpretative processes, before commencing with testing at eleven sites in 1991. Site selection criteria included geographic spread and sites that were used in a previous WDOH study (Faigenblum, 1988). Figure 1 shows the ten bacteriological and eleven chemical test site locations.

Marine Biotoxin — Sixteen sites were selected for PSP monitoring because of the reliability of site samplers (often commercial growers) and by geographic distribution throughout the Sound. Species varied from station to station. Locations for the testing of the marine biotoxin PSP are listed in Table 4.

METHODOLOGY

Bacteriological — During each sampling quarter, 90 native littleneck clams were dug from a 100 meter section of each beach site. Where conditions permitted, clams less than 3.7cm, or those with cracked shells, were returned to the beach. The 90 clams were sub-divided into small (3.7-4.3cm), medium (4.3-5.6cm) and large (greater than 5.6cm). Equal numbers of clams were taken from the three size groups to make up three replicated composite samples. This sorting methodology was designed to reduce field sample variations. The samples were packaged, coded and delivered in an ice chest to the WDOH Public Health laboratory.

The procedures followed at the laboratory included shell cleaning, removal of shell contents, sample blending and first dilutions, inoculation into culture medium, testing for fecal coliform bacteria, and estimating the most probable number (MPN) of organisms per 100 grams of tissue (APHA, 1970). The MPN lowest detection limit is 18 organisms per 100 grams of tissue.

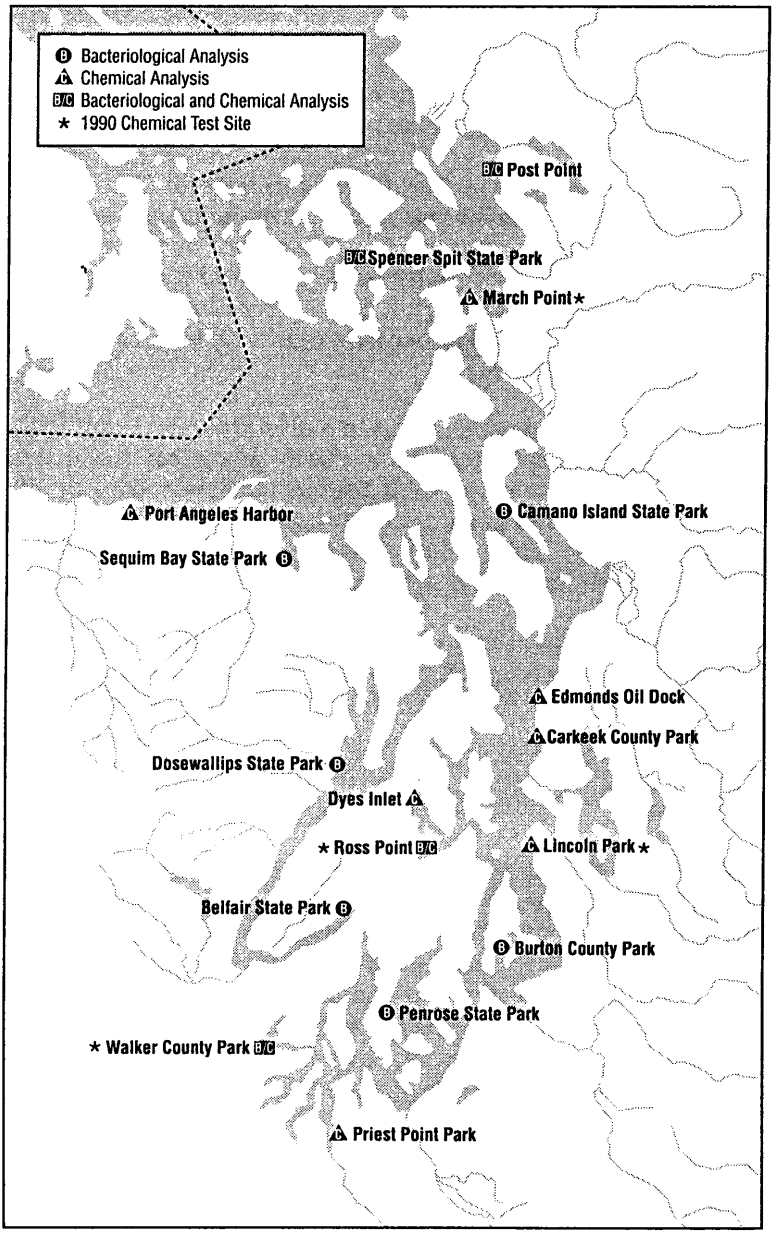

Figure 1.
BACTERIOLOGICAL AND CHEMICAL PSAMP SITES FOR 1990/91.

Chemical — Target species clams were gathered using the same protocols as bacteriological samples. Triplicate replicate composite samples were placed in acid-rinsed glass jars and then frozen.

Marine Biotoxin — The principal dinoflagellate causing PSP is *Alexandrium catenella.* Samples were sent to the WDOH Public Health Laboratory to be tested for the presence of toxins. After removal from the shell, PSP concentration in the tissue is quantified by a mouse bioassay (MBA) (APHA, 1984). The laboratory provides results as micrograms of toxin per 100 grams of tissue. The lower detection limit for the bioassay is 37 micrograms of toxin.

Prior to analysis, WDOH staff worked with the analytical laboratory of the Municipality of Metropolitan Seattle (METRO) to clarify analytical issues. WDOH subcontracted quality assurance and quality control (QA/QC) coordination and technical liaison between WDOH and METRO to a consultant, Dr. David Kalman, Associate Professor of Environmental Sciences, University of Washington.

METRO began analysis of the samples in October 1990. Puget Sound protocols were followed for six metals and a modified organic chemical EPA priority pollutant scan, plus some Hazardous Substances List (HSL) chemicals and several other compounds. In addition, method blanks, matrix spikes, replicate matrix spikes and validation experiments were also performed. A new National Institute of Standards and Technology (NIST) standard reference material (SRM), mussel tissue (#1974), was used for the organic chemical analysis. An oyster tissue SRM (#1566A) was used for metal analysis.

RESULTS

Bacteriology — Table 2 provides a summary of the MPN data. The range of MPN values is shown, as well as geometric mean, median and the log coefficient of variation (C.V.). The log coefficient of variation is calculated by dividing the log standard deviation by the log mean of the MPN values.

Also listed in Table 2 are the percentage of MPN values, by site, that fall into one of three MPN categories: <30, 31-230, and >231.

Chemical — Results are divided into metals and organic chemicals. Metal results show low levels at all sites. The ranges of metal values are listed in Table 3. Mercury values are compromised because analysis was begun after the required Puget Sound Protocol freezer holding times.

Table 2.
SUMMARY OF PSAMP BACTERIOLOGY RESULTS 1989-90.

SITE	N	(detection limit 18 organisms/ 100 grams) MPN RANGE IN TISSUE	GEO MEAN	MEDIAN	C.V.	MPN CATEGORIES (FC/100gm) <30	31-230	>231
Belfair	15	330 to 35,000	2,800	3,300	0.16	0	0	100
Burton	15	18 to 330	25	<20	0.38	73	20	7
Camano	15	<20 to 20	14	<20	0.14	100	0	0
Dosewallips	15	230 to 4,900	570	330	0.22	0	53	47
Penrose	15	18 to 1,300	30	<20	0.48	73	13	13
Post Point	14	<20 to 430	39	20	0.41	64	21	14
Ross Point	15	<20 to 170	30	20	0.28	53	47	7
Sequim Bay	15	<20 to 310	38	45	0.32	47	47	7
Spencer Spit	13	<20 to 330	56	62	0.30	17	83	0
Walker Park	15	78 to 4,900	1,100	1,100	0.17	0	13	87

Organic results are divided into two groups: 1) chemicals analyzed using gas chromatography and a mass spectrometer (GC/MS), and 2) pesticides and PCBs analyzed using gas chromatography and an electron capture device (GC/ECD).

1) **GC/MS.** Based on validation experiments, a nominal detection limit of 30 g/Kg or parts per billion (ppb) has been assigned for the majority of GC/MS chemicals (81 percent). Some EPA priority pollutants were missed in this analysis. Detailed explanations can be found in the technical report (WDOH, in prep.). At these detection limits, the four sites revealed no chemicals above detection values for GC/MS, except fluoranthene which was found in one of the March Point samples at 44 ppb.
2) **GC/ECD.** This analysis yields a complex data set that has many data qualifiers (see technical report for full details). For pesticides, analytical detec-

Table 3.
***MEAN METAL VALUES,** mg/kg or parts per million (ppm) wet weight, by site. Detection limits, mg/kg or ppm wet weight, in brackets.*

SITE	N	ARSENIC [0.5]	CADMIUM [0.02]	COPPER [0.02]	MERCURY [0.004]	LEAD [0.04]	ZINC [0.04]
Lincoln Park	3	1.6 - 1.8	0.20 - 0.23	1.0 - 1.3	0.010 - 0.012	0.094 - 0.11	11 - 12
March Point	3	1.5 - 1.6	0.18 - 0.18	0.96 - 0.97	0.016 - 0.018	0.059 - 0.077	10 - 11
Ross Point	3	1.4 - 1.7	0.14 - 0.16	1.3 - 1.4	0.018 - 0.028	0.12 - 0.15	14 - 16
Walker Park	3	2.0 - 2.1	0.21 - 0.23	0.98 - 1.0	0.014 - 0.016	<0.04	12 - 14

tion limits of 0.8 to 2.4 ppb have been assigned. Toxaphene and the Aroclor series of PCB's are less well characterized and have been assigned a higher detection limit. Data from the four sites shows DDE was found at Lincoln Park (triplicate samples contained 2, 2 and 3 ppb), Ross Point (2 ppb in one sample, trace amounts in the other two) and Walker Park (1 and 3 ppb in two samples); no DDE was detected at March Point.

Marine Biotoxin — The results from the sixteen stations are listed in Table 4.

DISCUSSION

Reduced funding resulted in a limited data set. Therefore the characterization potential of existing data for the Puget Sound is limited. However the monitoring has produced useful data for specific sites, and built a solid foundation for the second year of monitoring.

The data sets for the three different parameters should be coupled with other related data sets, before attempting detailed discussion of the results. The following factors are examples of related data sets that could impact results: meteorological conditions, tides and currents, local point and nonpoint sources, seasonal conditions.

Bacteriology — In the past, MPN results have had limited usage by themselves. This is because MPN tissue results have been treated as one component of a triad system for commercial regulatory public health shellfish decisions. The triad system involves MPN meat tissue results being used with two other data sets: MPN tests on shellfish growing waters, and sanitary shoreline surveys that include knowledge of local point and non-point sources. A 230 MPN value in commercial shellfish tissue is used by regulatory agencies as a signal that further testing of the meat is required.

A MPN value of 10 was used for <20 values in the statistical analysis. Tests of dependence using Chi-Square analyses indicate that seasonal effects, as assessed by quarterly sampling, do not have a significant ($\propto = 0.05$) effect on fecal coliform concentrations.

The coefficient of variation (C.V.) was calculated by site for the data set (see Table 2). The C.V. is a measure of the dispersion of results about the geometric mean. Camano Island had the lowest C.V. value, showing consistently low fecal coliform MPN values. Belfair and Walker Park also have a low C.V. value, but this reflects the consistency of high MPN values. Penrose had the highest C.V. value. Penrose is one of the beaches that will be more intensively studied in the next year to try to find reasons for the large MPN variations. Further statistical analysis of coefficients of variation is planned.

Table 4.
1990 PSAMP PSP RESULTS, BY SITE.

SITES*	N	SPECIES	APPROX. SEASON OF TOXICITY >80 ug	APPROX. DURATION OF TOXICITY >80 ug	1990 MAXIMUM TOXICITY	PREVIOUS TOXICITY >80 ug 1985 - PRESENT
Blyn, Sequim Bay	37	Native littlenecks	Late Oct. '89-Early March '90	4 months	134 ug	85, 86, 87, 88, 89, 90
Scow Bay, Kilisut Harbor	55 25	Native littlenecks, oysters	Late Oct. '89 - Med Feb. '90 Early Sept. '90-late Sept. '90	3.5 months 2-3 weeks	180 ug (littlenecks) 234 ug (oysters)	85?, 86, 89, 90
Drayton Harbor	10	Oysters	No toxin Det. > 80 ug		44 ug	85? 86? 87? 88?
Wescott Bay	15 37	blue mussels Oysters	No toxin detected	------	------	86
Ship Bay, Eastsound	44	Oysters	Mid- July '90 - late Aug. '90	5-6 weeks	734 ug	85, 89, 90
Samish Bay	74	Oysters	Late June '90 - mid-July, '90	3-4 weeks	1,371 ug	86, 87, 89, 90
Penn Cove	40	blue mussels	No toxin detected	———	———	None
Holmes Harbor	51	blue mussels	No toxin detected	———	———	85
Edmonds Oil Dock	10	butterclams	Late June '90 - Late July '90	1 month	230 ug	89, 90
Fauntleroy	11	blue mussels	Mid-June - mid-August, '90 Early Oct. '90 - ? '90	2 months unknown	989 ug 644 ug	86, 87, 88, 89, 90
Point Bolin, Agate Pass	9 16	butterclams, little necks	Late Sept. '90 - present '90	3 months	330 ug (littlenecks)	85? 86? 87? 88? 89, 90
Fox Island Bridge	22	blue mussels	Early July '90 - Mid Aug. '90 Late Sept. '90 - ? '90	5-6 weeks unknown	390 ug 176 ug	85? 86? 87? 88, 89, 90
Dupont Wharf	24	blue mussels	Late July '90	2 weeks	237 ug	85? 86? 87? 88? 90
Hartstene Island Bridge	5	blue mussels	No toxin detected	———	———	None
Skookum Inlet	10	manila clams	No toxin detected	———	———	None
Hamma Hamma River	11	oysters	No toxin detected	———	———	None

"?" indicates limited monitoring during the year(s).
* Final figures on number of samples available after December 31.
Oysters - Crassostrea gigas Manilas - Tapes japonica
Natives - Protothaca stamina Blue mussels - Mytilus edulis
Butters - Saxidomus giganteus

Because of the high MPN numbers gathered through PSAMP testing, Belfair State Park and Dosewallips State Park were both closed to public harvest of shellfish. At both these sites the Office of Shellfish Programs is involved with restoration activities. Other PSAMP sites with elevated MPN values are being more intensively investigated in order to identify contamination sources.

The MPN beach classification system (see Table 2) has potential as support data for recreational beach management planning. (A final management plan will be published in 1991.) By using local volunteers working with WDOH staff, PSAMP monitoring has potential for both increased environmental monitoring, and public education.

Marine biotoxin—No separate sampling effort is currently being made for the collection of PSAMP PSP data, because of the lack of funding. Instead the results of sixteen stations are transferred from the Office of Shellfish Programs regulatory PSP database to PSAMP databases. The Office of Shellfish Programs regulatory PSP program is primarily designed for regulating commercial and recreational harvest, not ambient monitoring. Consistent protocols for PSP sampling are difficult to achieve because PSP samplers are often commercial growers who sample only from beds that are about to be harvested. This can result in changes of species and frequency of samples.

Due to the above reasons the limited PSAMP PSP data cannot be used for trend analysis for the entire Puget Sound. An overview of the PSP levels in Puget Sound can be gained from the Department of Health report of 1990 PSP levels from approximately 120 stations (WDOH, 1991).

Please see the recommendations section for methodologies to improve PSAMP PSP monitoring.

Chemical — With a team approach between planners, toxicologists and laboratory, chemical analysis has been very useful and will be continued.

The new Standard Reference Materials values show the low levels of urban contaminants that can be found in East Coast bivalve tissue. Should PSAMP go down to these levels? If trend analysis is desired, what are the costs of this approach?. Health risk concerns might require new target chemicals at even lower detection limits. Answers to these types of questions will determine technological and methodological choices.

There is good correlation of metals values between PSAMP and the previous WDOH study (Faigenblum, 1988). Further comparisons between PSAMP metal and organic data and other studies will be made in the WDOH technical report (in prep.).

WDOH Office of Toxic Substances is preparing a report, entitled "Human Health Concerns Associated with Ingestion of Puget Sound Seafood." The report will utilize PSAMP data collected in 1990 by both the Department of Fisheries and Department of Health Shellfish Program. Original toxicological data is being reviewed to determine if the concentration of identified chemicals is of human health concern. Potential health effects will be discussed, along with measures to reduce the likelihood of such effects.

SUMMARY

In 1990, PSAMP shellfish testing for three parameters in shellfish tissue was completed. The three parameters are bacteria, marine biotoxins and chemicals. Data for ambient monitoring and public health protection has been generated. The second year of monitoring will build on the experience gained from the initial study, and increase the number of test sites for two parameters.

Ten Puget Sound beaches were sampled quarterly for fecal coliform concentration in *Protothaca staminea* (native littleneck clams). Four beaches were sampled once to determine chemical concentrations of a select number of metal and organic chemicals in *P. staminea.* Various shellfish species, from sixteen Puget Sound sites, were analyzed for concentration paralytic shellfish toxin produced by the marine dinoflagellate *Alexandrium catenella.*

Bacteriological results reveal a large range of fecal coliform concentrations. Fecal coliform levels varied at different times of the year and showed great site variation, reflecting the site specific nature of fecal coliform levels. As a result of PSAMP sampling, two recreational beaches, Befair State Park and Dosewallips State Park, were closed to public harvest, and restoration activities have begun.

Marine biotoxin results highlight the intermittent and unpredictable nature of PSP blooms and the need for continued monitoring, coupled with coordinated multi-agency research.

Chemical results were limited to four sites. Low levels of metals were found at all sites. Flouranthene and DDE were found at some sites. A quality assurance and quality control plan has been adopted that will improve the quality of data at the eleven 1991 sites. A new report from the Office of Toxic Substances will be released in 1991 which will begin to assess human health concerns associated with chemicals in shellfish.

RECOMMENDATIONS

Three categories of short- and medium-term recommendations are listed below. Long-term recommendations include the establishment of an international, low technology, shellfish monitoring program.

Increase communication and coordination

Establish mechanisms for increased sharing of related data between local, state and federal government agencies. West Coast and Canadian monitoring coordination should be a medium term goal. Educate data users about monitoring plan design and results.

Gather related data sets, which might impact interpretation of results and future sampling strategy, e.g. meteorological data and knowledge of chemical point source pollutants.

Plan and conduct a 1991 symposium to discuss the second year of PSAMP shellfish monitoring and other related studies. This symposium could become affiliated with the Washington State Environmental Health Association shellfish conference.

Expand monitoring

Full implementation of the original 35 site sampling plan is necessary. Increased funding, coupled with more citizen monitoring, will achieve this objective. If triplicate composite bacteriological sampling protocols could be reduced to duplicate composite samples, it would enable the PSAMP program to increase frequency and geographic spread of the sampling around Puget Sound. The beach field sampling protocol should be strengthened to ensure that samplers are digging from several locations on the beach.

Increase the usage of local environmental volunteers, working with WDOH staff. This represents an opportunity for schools, colleges and local environmental groups to gather shellfish and site data (which the state cannot presently afford to collect), e.g., size of shells, species abundance, MPN values from fresh water sources and meteorological data.

Methodologies

Bacteriology — Begin working with other laboratories for selective pathogen searches with samples from some PSAMP beaches. Vibrio species might receive particular attention because of recent renewed concerns of their presence in the Puget Sound. Experiment with pour plate techniques to evaluate fecal coliform concentration—split tests could be carried out on PSAMP samples.

Chemical — Add target chemicals to the existing EPA priority pollutant scan which reflect those that have been introduced to the Puget Sound marine system, e.g., a new generation of pesticides, alkyl tins, dioxin, alkyl PAH, etc.

The PSAMP committee should collectively address the issue of chemical detection limits. A detailed standard operating procedure should be developed for relevant chemical protocols.

Marine Biotoxin — Sampling protocols should be strengthened. The mussel cage program currently in use in certain areas of Puget Sound should be expanded to improve early detection of toxic blooms.

Encourage research to replace the mouse bioassay with newer detection technologies which will enable the Public Health laboratory to analyze more PSP samples, and begin testing for other marine biotoxins.

Increase communication with institutes of higher education, and other agencies, to encourage coordinated studies of marine biotoxins. For example, plankton monitoring would be relatively inexpensive and could greatly enhance understanding and warnings of blooms, and access to time-lapse satellite reconnaissance of PSP blooms at test sites could assist in understanding causes of blooms.

ACKNOWLEDGEMENTS

The first year of PSAMP shellfish monitoring represents a team effort by many WDOH staff, both in the Office of Shellfish Programs and Toxic Substances, and at the public health laboratory. Special thanks to the following persons, who have been willing to offer their expertise and guidance during the preparation of this paper: Mary McCallum, Frank Meriwether, Jack Lilja, Glen Patrick, Maryanne Guichard, Derry Suther, Frank Cox, Helen Seyferlich, Jac Davies, Gary Skow, Rebecca, Don Martin, Dave Kalman. All errors and omissions are, however, the authors'.

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PUGET SOUND NEARSHORE HABITAT INVENTORY PROTOCOL

Thomas F. Mumford, Jr., J. Anne Shaffer, Daniel Saul, Allison Bailey, Elizabeth Calvert[1]

INTRODUCTION

Nearshore wetland habitats are a net result of a suite of interacting environmental characteristics, such as water quality, substrate, temperature, salinity, silt load, hydrology, and processes and patterns of coastal drift, that determine the type and amount of vegetation (or lack of vegetation) in a certain area. These habitats serve a number of economic and research functions as well as ecological functions, including nesting, breeding or refuge areas for wildlife and fisheries, food web support, sediment trapping, and nutrient cycling.

Information regarding the distribution, type, and functions of wetland habitats is critical in making good management decisions. Local, state and federal regulatory and proprietary agencies require this information in planning, zoning, leasing and permitting activities. While the mapping and inventorying of habitats in uplands has been taking place in Washington for over a century, estuarine and marine habitats have only been poorly or incompletely inventoried. Mapping of functions and values has not even begun.

Existing inventories—the Coastal Zone Atlas (CZA; Washington State Department of Ecology, 1980), the Puget Sound Environmental Atlas (PSEA; Puget Sound Water Quality Authority [PSWQA]), and the National Wetland Inventory maps (NWI; US Fish & Wildlife Service [USFWS])—all suffer from outdated information, inadequate resolution, or inaccurate information, especially in subtidal regions.

The marine and estuarine portions of the NWI maps are not accurate enough for the state to make land use and resource management decisions. Essentially the only information in them concerns the presence or absence of vegetation in the intertidal areas and degree of inundation. They do not include any information about whether the aquatic beds are drift or attached vegetation or what types of vegetation are present. They do not include any nearshore floating kelp beds (*Nereocystis* or *Macrocystis*), nor do they distinguish eelgrass from other types of vegetation. These data are important.

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MATERIALS AND METHODS

Data from a variety of new and existing sources has been collected, analyzed, and incorporated into a prototype GIS. The overall flow of tasks is shown in Figure 1.

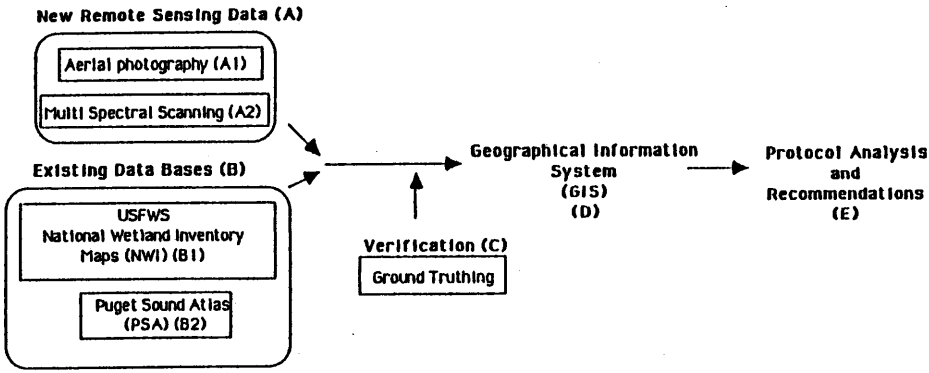

Figure 1.
PROTOCOL TASKS.

New remote sensing data have been obtained from aerial photography and from aircraft-based multispectral scanner (MSS) from six test sites representing a variety of habitats (Figure 1, Task A). Various scales and methods for classifying and transferring to a GIS have been examined.

The Bonneville Power Administration has digitized four photographs and tested the ability to classify these images using a microdensitometer and Eikonix digitizer at five different apertures and spacings. Existing data bases have been analyzed for the feasibility and cost of transferring them to ARC/INFO (Task B). Modified or updated NWI maps for eight USGS 15" quadrangles from the six test sites have been used as base maps for this study. In turn, the information from this study can be used by the USFWS to update and revise their NWI maps. The feasibility and usefulness of incorporated PSEA data also has been analyzed.

Verification has been accomplished by intensive ground truthing done simultaneously with remote sensing data acquisition (Task C). Ground truthing protocols have been developed. The project has analyzed the design, feasibility and costs of using a GIS system to store, analyze, and display information (Task D). Incorporating all these analyses has resulted in a recommended protocol for inventorying nearshore and salt marsh habitats and for performing long-term monitoring (Task E). In sum, the output is an analysis of data sources, their classification procedures, methods for their incorporation into

a GIS, and recommendations for an inventory protocol. Detailed data on habitat distribution and types are shown for the specific test areas.

This study is not directly concerned with habitat "quality"—the description and quantification of habitat functions and values. Future efforts must include inventorying the functions of these habitats, determining the annual variation in these habitats and their functions, and documenting long-term changes of habitat and functions. Under a separate but closely coordinated project, Dr. R. Thom has reviewed existing kelp and eelgrass inventory and mapping efforts and performed a trend analysis of kelp and eelgrass distribution (Thom and Hallum, 1990).

Two additional methods for wide-scale inventory taking were considered for this study but were discarded as unfeasible. The first—satellite-based multispectral imagery—was rejected because the resolution was insufficient (30 m for multispectral images) considering the size of the habitats to be classified. Moreover, the set timing of infrequent flyovers and the rigid requirements for weather, tide and daylight conditions make getting data very risky (see Webber et al., 1988 for discussion). The second method was the use of large numbers of people to survey beaches on foot. Factors working against such an effort include high cost (even if using volunteers) for training and data analysis, a very low degree of repeatability of classification between different people at the same time or between the same people at different times, and lack of any archival records (photos, digital data, etc.) which could be analyzed later using different techniques. However, such a method for transect work in a number of reference sites should be considered.

The geographic area/boundary of the study includes Puget Sound north to Canadian boundary, the San Juan Islands, the Strait of Juan de Fuca to Port Angeles, and Hood Canal. Habitats included in the study are marine, estuarine, and fringing salt marshes. Six protocol development sites were chosen. The criteria for selection are shown in Table 1. Figure 2 shows a large-scale map of Puget Sound with the six chosen test sites.

Habitat Classification System

Dethier (1990) has developed a regionalized classification system. It is a hierarchal system.

System — Marine or Estuarine
  Subsystem — Intertidal or Subtidal
    Class — Consolidated, Unconsolidated, Artificial or Reef
      Subclass — Substrate
        Energy Level
          Modifiers (depth, salinity, inundation freq.)
            Diagnostic Species/Dominance Type

The representation of these classification elements in a GIS is shown in Figure 3.

Accuracy Assessment Methodology

The test selected to assess the accuracy of the maps produced by the various methodologies is based upon acceptance sampling, a branch of statistics used extensively in the manufacturing industry for quality control. The application of this testing methodology to land cover maps is widely described in the remote sensing literature (Aronoff, 1982a, 1982b, 1985; Congalton and Russell, 1988; Ginevan, 1979; Story and Congalton, 1986). The basic criteria of acceptance sampling applied to remotely sensed maps are:

1) There should be a low probability of accepting a map of low accuracy;
2) There should be a high probability of accepting a map of high accuracy;
3) A minimum number of reference data sample points should be required to establish a level of confidence for the test results.

The method to test map accuracy is to select a sample of map points, collect "ground truth" or equivalent reference data at each sample point location, compare the classified maps to the reference data set at the sample points, and then make a statement about the true accuracy of the map.

Table 1.
CRITERIA FOR SELECTION OF PROTOCOL DEVELOPMENT SITES FOR THE NEARSHORE HABITAT INVENTORY.

1. Contain representative habitats based on a regionalized Cowardin classification - at least:
   1) Floating kelp (*Nereocystis*)
   2) Eelgrass (*Zostera* spp.)
      a) extensive beds (e.g., Skokomish)
      b) strip beds, (e.g., Fauntleroy Cove/Lincoln Park)
   3) Unconsolidated beaches/spits/flats
      a) rock/seaweed
      b) boulder/seaweed
      c) cobble/seaweed
      d) gravel
      e) sand
      f) mud
   4) Vegetated salt marshes
2. Sites should serve as long-term protocol reference sites,
3. Should be in different geographical regions, and
4. Should contain as many habitat types as possible within a short distance.

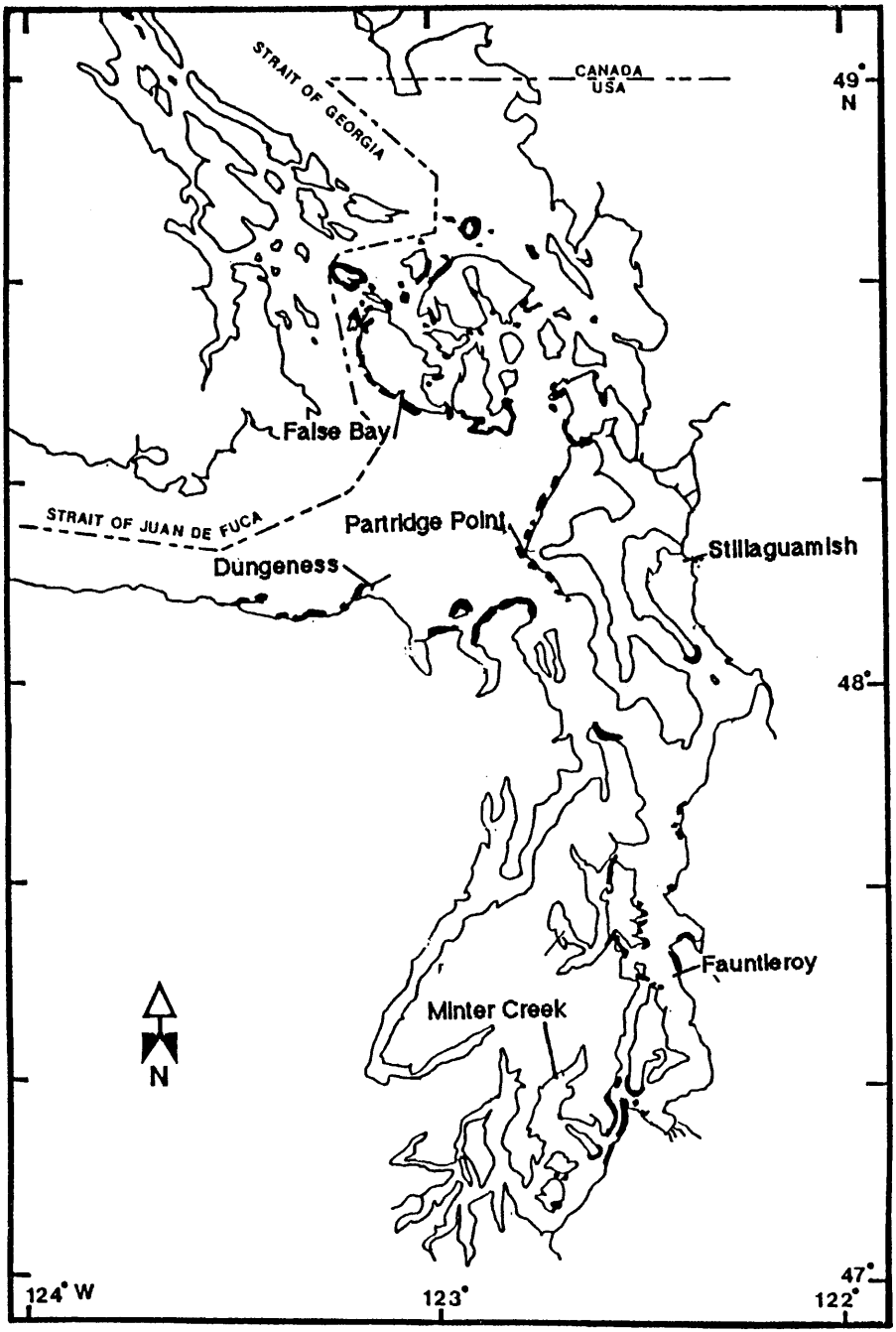

Figure 2.
SIX PUGET SOUND SITES CHOSEN FOR REMOTE SENSING DATA ACQUISITION.

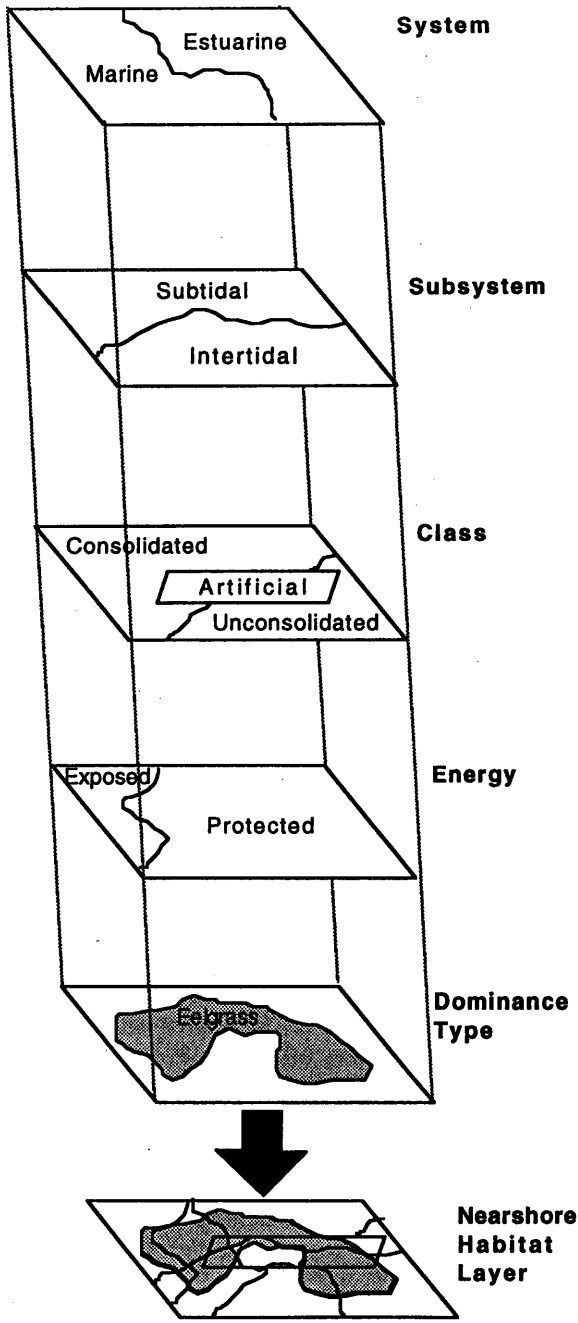

Figure 3.
GIS REPRESENTATION OF THE ELEMENTS OF THE NEARSHORE HABITAT LAYER.

RESULTS, ANALYSIS AND RECOMMENDATIONS

Ease of Data Acquisition

The acquisition of aircraft-borne remote sensing data, by either aerial photography or multispectral scanner, for this application remains problematic. To have a combination of clear weather, calm seas, a tidal level below -1.0 ft, summer growing season, and correct tidal levels between approximately 8am-4pm for good sun angle in the Pacific Northwest calls for luck, but it is feasible. We were able to collect over 60% of the data for the entire Sound during a 30 day period (two low tide series) in 1988, and future efforts call for only 33% to be gathered per year. Aircraft have the distinct advantage over satellite of being able to fly when conditions are suitable, not just when the orbit goes over the area once every 17 days. The availability of aerial photography-equipped aircraft is good; local contractors can easily be found. There are additional charges for remaining on standby during low tide series.

However, georeferencing remains a problem for aerial photography in this application. To get a suitable number of control points for stereo plotting, about 2/3rds of the photo must contain land. However, this application works best, when flown at 1:12,000, when only about 1/3rd of the photo is land. This allows optimal coverage of offshore areas such as kelp and eelgrass, as well as coverage of irregularities in the shoreline.

Accuracy Assessment Results

Map accuracy results are shown in Table 2. In general, the overall accuracies are about 60% in unmodified data, and probably no significant differences exist between methods. Zoom transfer method accuracies are high, but all areas were not 100% mapped (especially substrate), and the method throws away data points outside of classified areas, leading to bias in "truth". Also, by using the CIR photos as "truth," there is a bias towards CIR-based methods. Multispectral scanning accuracy is biased towards being too low because of #2 and #3 above. There is great potential for improvements in accuracy of MSS, as substrata, especially moisture gradients, are well classified in this system. However, vegetation classification needs further refinement, and texture is not well done in MSS. It was impossible to separate georeference and classification sources of error.

Analysis of Costs and Feasibility of All Steps and Their Interactions

Table 3 shows the application of seven selection criteria to the data acquisition methods employed.

Table 2.
SUMMARY ACCURACY ASSESSMENT MATRIX. *Numbers in matrix are overall accuracy estimates (%) from confusion matrices. Summary statistics generated using arcsin transformation.*

1. All classes:

SITE	ZT 1:6000	1:12000	PI * 1:12000	MSS UNEDITED	EDITED
DUNGENESS**	68.32	40.19	43.32	36.14	53.5
FALSE BAY	55.34	33.33		58.45	61.92
MINTER CREEK	86.25	81.41		52.39	67.49
PORT SUSAN	NA	81.19	NA	NA	NA
X***	70.89	60.20		48.94	61.04
S***	10.17	15.75		6.68	4.14

2. Vegetation only:

SITE	ZTS 1:6000	1:12000	PI * 1:12000	MSS UNEDITED	EDITED
DUNGENESS **	72.65	55.38		48.46	73.8
FALSE BAY	65.61	63.55	49.57	67.46	
MINTER CREEK	88.09	93.97		85.47	94.59
PORT SUSAN	NA	NA	NA	NA	
X***	76.18	73.33		62.32	80.33
S***	8.10	14.80		13.39	11.34

* *EPA's Photo interpretation compared to DNRs stereoplotter maps*
** *DNR's stereoplotter map used for accuracy assessment*
*** *Generated using arcsin transformation*

Protocol Recommendations

Data acquisition — Digital imagery should be acquired using an aircraft-based multispectral scanner. The plane must be equipped with Global Positional Satellite (GPS) and Internal Guidance System (IGS) or gyroscope for simultaneous position and attitude data recording with the image data stream. The digital data must then be able to be georeferenced to ±1 pixel. The data should be acquired during June, July, and August when the tide is at least at -1.0' below MLLW (datum), in 4-5 m pixel resolution. Simultaneous color infrared 9" color positive and standard color photographs of smaller format with 60% overlap for stereo pairs must be taken.

Data analysis — Ground truthing should be performed by inspecting priority areas on the ground to annotate photos and rough MSS images. Final images are corrected as needed. Image analysis is performed by using unsupervised classification and within-class classification after masking out uplands and water. We suggest using ERDAS image processing software.

Table 3.
SELECTION CRITERIA APPLIED TO MOST VIABLE COMBINATIONS OF TECHNOLOGY.

	Color Infrared Photos			MSS	Ground-based Analysis
	Photo interpretation Stereoplotter	Photo interpretation Zoom Transfer Scope	Digitizer		
Aircraft availability	High	High	High	Low	NA
Costs	454,000	382,100	483,500	433,500	?
Positional Accuracy	±1 m	± 15-76 m	Medium	±25m ±2.5m	±30 m
Classification Accuracy	High	High	Medium	High	High
Time to interpret	High	High	Medium	Low	High
Repeatibility	Low	Low	Low	High	Very low
Future Developments	•mirrow stereoscope •GPS	None	•high resolution •better digitzation •faster image analysis	•GPS/IGS •resolution •# of channels •faster/ cheaper image analysis •fluorescent line imaging	Use GPS to locate positions

Classification — Dethier's modified Cowardin Classification (Dethier, 1990) should be used for consistency.

Products — The products of the project will be updated marine and estuarine systems on NWI maps, with data stored in an ARC/INFO vector-based GIS.

Implementation of the protocol is moving forward. DNR has contracted with EPA-EMSL to convert the entire MSS data set collected in 1988 to computer-readable tapes. It has purchased a SUN SPARC-1 work station with UNIX-based ARC/INFO and ERDAS image processing software, processed much of the 1988 MSS data, and included it in the Aquatic Lands GIS (ALGIS). In addition, DNR has performed a user survey to determine priorities for areas to be analyzed first. DNR has agreed to work with PSWQA to maintain the Puget Sound Environmental Atlas, and is requesting funds for the next biennium (July 1991-June 1993) through the PSWQA plan to continue monitoring. DNR has contracted EPA-EMSL MSS plane time during the summer of 1991 to acquire data for one third of Puget Sound.

DISCUSSION

Several areas will require continued effort. We need to focus on further refinement of image processing/classification. We are working on a cooperative effort with EPA-EMSL for refinement of accuracy assessment.

We need to complete reference site or transect protocols. Dethier's regionalized classification will be continuously refined, and the USFWS should be convinced to adapt it. There will be an ongoing coordination effort with all users to provide habitat information. And over the long term, we will begin the task of progressing from physical habitat description and mapping to the description and mapping of the functions of these wetlands.

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The specific companies and products mentioned in this paper are provided strictly as a convenience to the reader. Any mention of a specific company or product does not constitute endorsement by the Department of Natural Resources, and the DNR reserves the right to refuse listing any product or company.

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THE PUGET SOUND AMBIENT MONITORING PROGRAM DATA MANAGEMENT SYSTEM

Roberta P. Feins[1]

INTRODUCTION

In developing the Puget Sound Ambient Monitoring Program (PSAMP), the Environmental Protection Agency, the Puget Sound Water Quality Authority (the Authority), and the Monitoring Management Committee recognized the importance of setting up a system to manage program data. A needs assessment was conducted as part of PSAMP design, and the development of a PSAMP data management system (hardware, software, computer programs, data, procedures, and organizational arrangements) was recommended (Monitoring Management Committee, 1988a).

This paper discuss the structure of the PSAMP data management system, progress in system implementation since the PSAMP design was adopted in 1988, and ways that PSAMP efforts are coordinated with other efforts currently underway in Washington State to better utilize environmental data.

THE PSAMP DATA MANAGEMENT SYSTEM

PSAMP goals are to characterize background conditions in Puget Sound, identify problem areas, define past trends, and predict future conditions. In order to achieve these goals, a data management system must:

- meet present and long-term needs for environmental information on Puget Sound;
- integrate data from PSAMP with important historical information and data from other ongoing monitoring programs;
- provide the flexibility to meet a wide variety of needs for information from users (including PSAMP personnel in different implementing agencies, agency managers and decision makers, research scientists, and the public); and
- support ongoing agency regulatory and resource management activities.

A fully funded PSAMP program will collect about 206,000 pieces of data each year. The data management system must be able to store this information and allow it to be used and displayed in different ways. In addition, the system must keep track of the information and ensure that it is adequately documented, and its quality carefully maintained.

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The PSAMP data management system (Figure 1) consists of:

- distributed databases and paper archives maintained by implementing agencies;
- a central database for integrated data analysis and reporting;
- standard protocols used for sample collection and analysis, and standard transfer formats used for data exchange; and
- a Geographic Information System to allow geographic analysis and presentation of data on easily-readable maps.

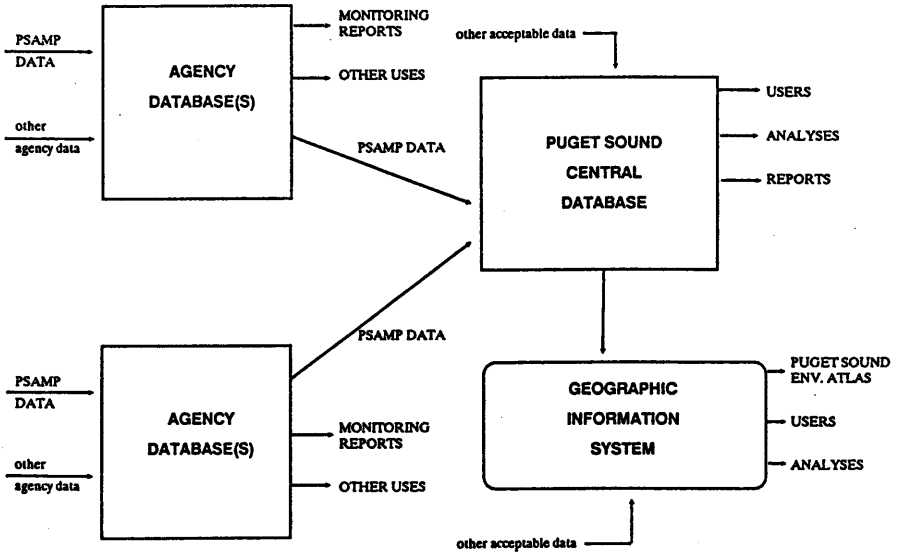

Figure 1.
FLOW OF INFORMATION IN THE PSAMP DATA MANAGEMENT SYSTEM.

Agency Databases

Each implementing agency will maintain a computerized monitoring database of PSAMP data, along with appropriate documentation. This computerized database will be used to analyze data, produce annual monitoring reports, and meet other regulatory and management needs of the agency. Data will be transferred to other software for producing formatted tables and graphs, and for conducting standard or non-standard statistical analyses. Data from agency databases will be sent to the PSAMP central database as each year's monitoring is complete.

Detailed implementation plans developed for each task include a description of the hardware, software, database management system and procedures the

implementing agency plans to use in managing task data (e.g. see Pepe, 1990). Costs for purchasing hardware and software, for hiring programmers to develop new databases or modify existing ones, and for organizing, entering, verifying, and managing each year's PSAMP data were built into each agency's monitoring budget during initial PSAMP development. Since PSAMP was not fully funded, several agencies have not been able to, or have chosen not to, begin system development.

Other agencies have moved ahead with database implementation. The Washington Departments of Ecology and Fisheries are using customized configurations of the PSAMP central database to manage sediment and fish monitoring data. The Department of Ecology is using an existing database (written in dBase IV) to manage data from the PSAMP marine water column and freshwater tasks. The Washington Department of Health is planning to develop its PSAMP database in RBase, as part of its Shellfish section database. These databases use or will use IBM compatible microcomputers which provide considerable processing power at affordable hardware and software costs.

PSAMP Central Database

The PSAMP central database will store and integrate data from PSAMP tasks, selected historical data, and data from other Puget Sound programs. The database consists of a computer (A COMPAQ computer with an 80386 processor and 300 megabytes of disk capacity), software (dBase IV), data files, and a set of menu-drive programs that manage the data. Data will be transferred to other software for producing formatted tables and graphs, and conducting statistical analyses.

A system developer and a programmer have worked on system development for a total of 3 1/2 person-years. The time has been necessary to develop a useable system that carefully documents and maintains data, and is flexible enough to handle the wide variety of PSAMP data types. The menu-drive database has the following functional modules:

- Add/Edit — Allows full-screen data entry and validation.
- Load — Loads data in PSAMP formatted ASCII files into the PSAMP database.
- Verify — Performs a series of verification checks on entered or loaded data.
- Derive — Calculates and stores summary information from loaded data.
- Reports — Produces a variety of standard and custom reports.
- Transfer — Outputs data from database in PSAMP formatted ASCII files for transfer to other databases.
- Utilities — Performs a set of data maintenance operations.

Data files and forms have been built for the PSAMP sediment, fisheries, shellfish, freshwater, and water column tasks, and remain to be built for the marine mammal and bird tasks. A user's manual and a system manager's manual have been developed.

Data from 1989 PSAMP sediment monitoring and from several historical surveys have been loaded into the database. In 1991, PSAMP data from 1990 and selected historical data will be obtained and loaded.

While original PSAMP plans called for linking together PSAMP computers and allowing remote access to the database via modem, funding has not been available to develop these links. Data exchange can still occur using floppy disks, however, and electronic links can be developed in the future, should funding become available.

Protocols and Data Transfer Formats

PSAMP design requires the use of standard protocols for sample collection, analysis and quality control. The Puget Sound Protocols and Guidelines (Puget Sound Estuary Program, 1986) must be used for PSAMP sampling.

A set of formats for transferring PSAMP monitoring data among agencies were developed in 1988 (Monitoring Management Committee, 1988b). Such formats detail the information, format, and order of data to be contained in ASCII files used for data transfer. These formats describe a common language for sharing information, regardless of the nature of the originating database. Data transfer formats are available for all of the PSAMP tasks, except for nearshore habitat.

The PSAMP central database contains a set of programs to allow data to be loaded from files in this data transfer format; agency databases will also have the capability to output and possibly input data in this format. However, the need for standards for data collection and exchange goes beyond the PSAMP program; there is a strong need to integrate monitoring data from a variety of Puget Sound programs. The 1991 Puget Sound Water Quality Management Plan (Puget Sound Water Quality Authority, 1990) requires the use of Puget Sound protocols and guidelines and PSAMP data transfer formats for NPDES monitoring information, watershed monitoring data, intensive survey information, and information from other Puget Sound monitoring programs collected by Federal, state, local agencies and tribes. The requirement to use PSAMP data transfer formats will involve some minimal costs to agencies to add capabilities to existing or new databases so that data files in PSAMP data transfer format can be produced and loaded. However, the ability to freely exchange information on Puget Sound will be a major benefit to all agencies with an interest in or responsibility for Puget Sound.

A Geographic Information System

A geographic information system (GIS) is a computerized tool for managing layers of different types of information so that the information can be analyzed and mapped in a variety of scales and formats. GIS is expensive technology, and it would not be possible to develop a GIS for PSAMP alone. In 1989, the Authority adopted a recommendation (Feins, 1989) for the creation of an integrated Puget Sound GIS. Such a GIS, containing data of intermediate scale appropriate for regional analysis and covering the entire Puget Sound watershed, would enable analysis of PSAMP data and would support the implementation of the Puget Sound Water Quality Management Plan.

In 1990, the U.S. Geological Survey, under a cooperative agreement with the Authority, obtained digital data from existing sources, transferred the information into Arc/Info software, and created a set of properly designed GIS data layers. An interagency Puget Sound GIS working group oversaw this effort. A list of priority data types (Table 1) was developed through surveys of potential data users (Feins, 1990a). So far, only a limited number of these have been included in the GIS.

The Department of Natural Resources Division of Aquatic Lands is currently planning to develop a GIS to manage data from the PSAMP nearshore habitat inventory (EMSL, 1990), and data needed for managing state aquatic lands. The 1991 Puget Sound Water Quality Management Plan (Puget Sound Water Quality Authority, 1990) calls for DNR Aquatic Lands to serve as a long-term home for the Puget Sound GIS, and requests funding for system maintenance in the next biennium. In 1991, the Authority and Aquatic Lands plan a project to update and republish the Puget Sound Environmental Atlas (Evans-Hamilton and D.R. Systems, 1986).

In the long-term, no single state agency will have the resources, the political clout, or the expertise to successfully develop an integrated GIS like the Puget Sound GIS. Rather, such a GIS will probably consist of linked sets of information maintained by agencies with the proper technical expertise, and designed to be compatible with, and integrated with information from other agencies. Several recent PSAMP projects have been designed to encourage the development of linked data sets:

- Several interagency working groups are currently meeting to agree on standard data definitions for such estuarine data types as bathymetry, habitat type, and shoreline.
- The Portage Creek GIS pilot project used GIS to organize information to evaluate nonpoint source pollution in a small Puget Sound watershed. Project results (Feins, 1990b) indicate that data sharing and use of GIS can greatly enhance the ability to analyze and see patterns in project data.

Table 1.
PRIORITY DATA TYPES FOR THE PUGET SOUND GIS

ESSENTIAL BACKGROUND DATA

* Shoreline
* Puget Sound Basin Boundary
* Embayment boundaries
* Political Boundaries

HIGHEST PRIORITY DATA TYPES

Point Source Discharges
Wetlands
* Shellfish Resources
* Rivers and streams, lakes
Bathymetry

OTHER PRIORITIES

* Marine Fish Resources
* Salmon Resources
Sediment Grain Size
* Major land use types
Waterfowl and Seabird Nesting Areas

LOWER PRIORITIES

* Watershed Boundaries
Dredged material disposal sites
Wildlife Refuges and Sanctuaries
Parks and Recreation areas, beaches
Marine Mammals
Major aquifers
Water currents

POINT DATA TO BE COMPILED AS PART OF MONITORING DATABASE

Shellfish contaminants
Sediment Chemistry Monitoring Data
Bioaccumulation
Diseased Bottomfish
Sediment Amphipod Bioassays
Abnormal Benthic Communities

** These data layers will be available by January 1991*

PSAMP staff are also working to coordinate Puget Sound GIS development with other efforts within Washington State. In 1990, the Department of Information Services formed a state Geographic Information Council to provide a forum for discussion and resolution of issues related to state-wide GIS development. (Geographic Information Council, 1990). In addition, the Department of Community Development (DCD) Data Advisory Group recently reported to the Legislature (Department of Community Development, 1990) on information needed to carry out the 1990 Growth Management Act. Their report indicates a tremendous need for data and a strong interest in GIS by local governments. Both DCD and the Geographic Information Council are strongly in favor of inter-agency cooperation and data sharing; however, specific recommendations or data standards have yet to be developed.

CONCLUSION

The PSAMP data management system, as designed and implemented, meets PSAMP program goals to maximize agency "hands-on" access to data, while ensuring high-quality, reliable, compatible data. Data can be integrated, analyzed and presented in reports tailored for the general public, as well as technical reports addressing specific issues. Data can be provided to agencies, researchers, and the public for their use. Data from other sampling programs in Puget Sound can be utilized, and monitoring information can be exported to other existing and planned databases to meet regulatory needs.

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THE EFFECTIVE CITIZEN MONITORING PROGRAM

Susan M. Handley[1]

The mission of a citizen monitoring program is to create an attitude of stewardship of Puget Sound and an opportunity for personal involvement among the citizenry of the area. A secondary mission is to support and enhance the work of state agencies involved in monitoring activities.

Under the direction of the Puget Sound Ambient Monitoring Program (PSAMP), the Puget Sound Water Quality Authority (PSWQA) has developed and funded two models of citizen monitoring programs. The goals of these programs were to (1) collect samples as part of PSAMP, and (2) to demonstrate the effectiveness of trained volunteers in monitoring efforts. Characteristics of effectiveness are clear job descriptions, a planned recruitment program, appropriate placement of volunteers, adequate training, ongoing support for and communication with volunteers, recognition of volunteer contribution, and an evaluation process for the program (Wilson, 1976).

This paper will discuss the preliminary results of citizen involvement in monitoring, the effectiveness of the programs, and the application of these models to other situations.

METHODS

In 1989, $50,000 was allocated from the Public Involvement and Education Fund (PIE) to promote and support citizen involvement in monitoring activities in and around Puget Sound. The PIE Fund is a 1.1 million dollar fund administered by PSWQA.

Following a publicized request for qualifications, two organizations, Adopt a Beach and Chautauqua Northwest, were selected as the contractors. Adopt a Beach, which had previous experience using citizen volunteers in monitoring activities, was selected as the model for involvement of traditional environmental programs. Chautauqua Northwest was selected as the model for involvement of an organization with little knowledge of or experience in environmental programs.

Adopt a Beach was contracted to assist the Washington State Department of Health with the collection of shellfish samples for analysis as to the presence of paralytic shellfish poisoning toxins. Citizen volunteers collect shellfish samples at twelve sites around Puget Sound ten months a year.

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Chautauqua Northwest was contracted to assist the Department of Health with the collection of shellfish for analysis as to the presence of bacteria. Citizen volunteers are to collect samples at three sites on a quarterly basis. Chautauqua also contracted to perform additional, undefined monitoring assignments when requested by state agencies and agreed to by PSWQA and Chautauqua. Under this agreement, Chautauqua assists the Washington State Department of Fisheries with the collection of fish for population counts and chemical analysis. They also assist the U. S. Environmental Protection Agency with computer mapping of discharge permit locations.

These two models differ in their approach to volunteer recruitment, training and communication. Adopt a Beach recruits volunteers who reside near the sampling site. There is one staff coordinator who is based in Seattle and who provides training, support and feedback to the 45 volunteers. The Coordinator is required to travel to different communities to recruit and train the volunteers. Training of the volunteers is held in local areas as new volunteers are recruited. The volunteers collect samples twice a month for seven months and once a month for two. There has been a total of 16 collections thus far in the program. The volunteers deliver the samples to a local site for transportation to the lab. Communication is maintained by a newsletter which is mailed to all participants, and by phone contact.

Chautauqua Northwest recruits one team of 20 volunteers from their membership. This membership of 500 people consists of retired business and community leaders. The recruited team travels to two different collection sites in the northern Puget Sound region. Training is scheduled in Chautauqua's office in Seattle. The team collects the samples four times a year and delivers them to the lab for analysis. To date there has been a total of 7 collections. The volunteers deliver the samples to the Public Health Laboratory in Seattle. Communication is maintained through personal and phone contacts.

The major cost of both programs is program administration. Volunteers working with the Chautauqua Northwest program are reimbursed for their travel expenses. The program administrator of Adopt A Beach is the only administrator to receive expense reimbursement.

Tasks and assignments for both models come through the Citizen Monitoring Coordinator (CMC). The CMC works with state agencies represented on PSAMP and local governments to define appropriate monitoring assignments, and then makes those assignments to the appropriate group.

RESULTS

Sixty-five volunteers connected with these organizations have been involved in citizen monitoring activities over the last two years. Of the twenty volun-

teers originally trained with Chautauqua Northwest, 100% are still involved. Of the forty-five volunteers trained by Adopt a Beach, 85% are still involved. This gives an overall retention rate of 93%.

The number of hours donated by the volunteers, including travel time and planning, is approximately 2620. In total, the volunteers have completed 239 sampling digs to collect shellfish. The two assignments to catch fish were not successful in getting the needed number of samples. To date the Chautauqua program has cost $14,919 and the Adopt A Beach program $20,678. This computes to $148.94 per collection dig.

UNANTICIPATED RESULTS

Interest of the press and media in the involvement of seniors has been an unexpected result of the program. There have been two televised segments on the Seniors for the Sound Program, a feature article in *Maturing Magazine*, and newspaper coverage of the program. In December 1990 CNN News carried a story about the Chautauqua volunteers involved in the program.

Unsolicited requests from organizations for potential involvement in the program has been another unanticipated result. Three organizations have contacted the CMC for volunteer participation and two for potential contribution of funds.

CONCLUSIONS

Programs have been successful in terms of meeting the program goals to (a) involve citizens and (b) collect shellfish samples. While the volunteers' efforts did not produce the required fish samples, they did generate data on species presence which was useful to the Department of Fisheries.

The established characteristics of effective volunteer programs are evidenced in both the Adopt a Beach and Chautauqua Northwest programs. Both programs have a designated program administrator and try to design the program to meet the volunteers' needs. Both have written job descriptions, follow a planned recruitment program, interview potential volunteers to assure appropriate placement, provide orientation and on-going training, provide the volunteers support, maintain consistent communication with the volunteers, have a planned volunteer recognition, and evaluate their programs at appropriate intervals.

CHALLENGES

The major challenge facing state agencies and programs, one which needs to be addressed if these programs are to be expanded or replicated, is the inexperience among State agency staff regarding volunteer involvement. This inexperience has resulted in initial resistance to volunteer involvement and inappropriate interactions with volunteers.

A suggested method to address this challenge would be the development and implementation of a training program for staff to encourage the appropriate use of volunteers. Understanding the volunteer perspective and realistic expectations for a volunteer program would be the key components of such a training program. This training program could also serve as an orientation for the state environmental program staff who would like a volunteer component but feel the effort would not warrant the results. There is a library of such training curricula available at no charge from the Washington State Center for Voluntary Action. The State Center also has a list of qualified trainers who could provide the training.

The challenge facing the volunteer-based organizations is to design programs to be more cost effective so that they are not dependent on a large contract or grant. Volunteer programs do require expenditures of funds; however, more effort could be placed on cost reductions to maximize available funding.

A suggested method to address this challenge would be to utilize volunteers in program administration and planning.

The second challenge facing the volunteer organizations is to design programs to respond to the increasing demand for involvement by the citizens of the Puget Sound region.

A suggested method to address this challenge would be to increase the flexibility of the programs in order to allow more sites to be included as sampling locations and to provide more opportunities for individuals and groups to design a local program which has shellfish collection as a part of their larger program. A pilot project, entitled the Beach Docent Program is based on this rationale and will begin in early 1991. The Beach Docent Program will be housed in the PSWQA office and be administered by the Citizen Monitoring Coordinator.

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PUGET SOUND

RESEARCH '91

SEDIMENTS: CONTAMINATION, REMEDIATION AND DISPOSAL

Session Chair:

Jack H. Gakstatter, U.S. EPA, Region-10

INTRODUCTION

Jack H. Gakstatter[1]

Sediment contamination has been a focus of the Puget Sound program since it began in the early 1980s. In fact, it was the association between sediment contamination and tumors in bottomfish that was largely responsible for getting the program started. In this session we are fortunate to have five papers which address various aspects of sediment contamination, remediation, and disposal in Puget Sound.

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NATURAL SEDIMENT RECOVERY IN CONTAMINATED EMBAYMENTS OF PUGET SOUND

Clayton R. Patmont[1] *and Eric A. Crecelius*[2]

INTRODUCTION

Sediments are often the predominant recipient of potentially toxic chemicals discharged into aquatic environments. Particularly for trace metals and persistent organic compounds, releases are readily sorbed onto and accumulate in aquatic sediments. Accumulations are often most pronounced in shallow, nearshore locations close to the point of release.

Adverse biological effects (or the potential for effects) associated with such chemical accumulations have been reported in a wide variety of nearshore locations. These effects include acute toxicity to sensitive species, changes in community structure, and the development of liver lesions in bottom-dwelling fish. As our understanding of the potential environmental risks posed by sediment chemical accumulations has advanced, so too have state and federal agencies developed regulations which require cleanup of these areas.

Based in part on the perception that sediment environments are quiescent, slowly changing systems, natural recovery (following adequate source controls) has often been discounted as a viable method of sediment remediation. Instead, many sediment cleanup programs conducted to date have relied on isolation (e.g., capping) or removal (e.g., dredging) technologies to improve local sediment quality conditions. While such techniques are appropriate in some situations, isolation and removal technologies applied over large areas are typically very expensive (often upwards of $100 million), and result in pronounced short-term biological impacts. In recognition of these concerns, the ability of ecosystems to recover naturally from chemical releases is being increasingly addressed as a component of overall sediment cleanup programs.

This paper discusses some important considerations of natural sediment recovery evaluations, examining several shallow embayments in Puget Sound, Washington. These embayments are currently targeted for remediation under state and/or federal Superfund programs.

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BACKGROUND

The rate of natural ecosystem recovery from chemical risks is closely tied to the chemical residence time within that ecosystem, particularly if the degree of effect or risk is related to chemical concentration (Boehm et al., 1985). The chemical residence time (T), in turn, can be defined as the inventory of a given chemical (I), divided by the mass rate of input or removal to an environmental compartment (dI/dt; e.g., in the sediment mixed-layer):

$$T = I/(dI/dt)$$

The capacity of sediments to initially assimilate chemical releases and later to recover from such accumulations is dependent on a number of physical, chemical, and biological processes. Among the more important processes are sediment deposition, surface resuspension and associated advection, diffusion (including bioturbation), sediment/water partitioning, biodegradation, and photolysis (Thomann and DiToro, 1983; Figure 1). Together, these processes largely define the mass rate of input or removal to and from the sediment/water system, and thus determine chemical residence times.

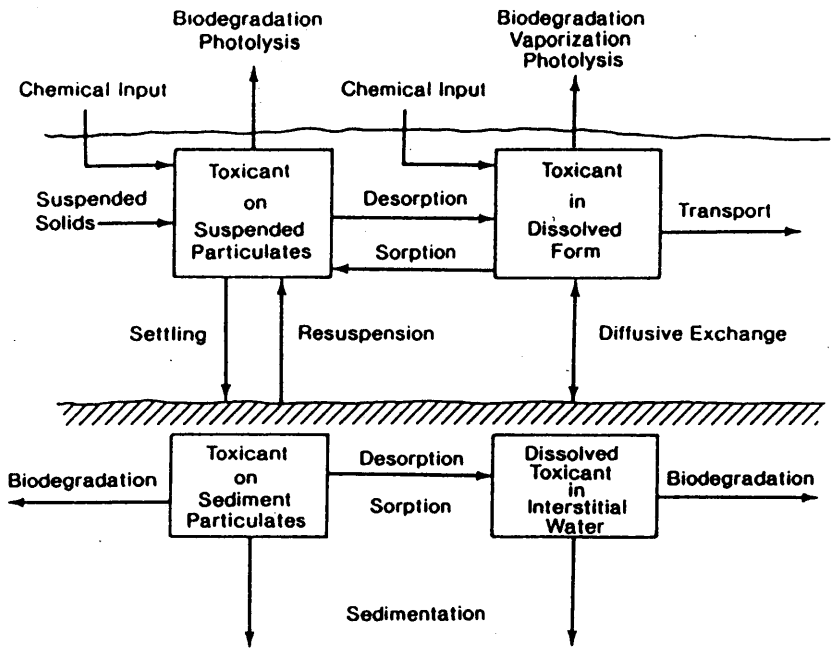

Figure 1.
GENERAL SCHEMATIC OF CHEMICAL FADE IN SEDIMENT SYSTEMS.
Adapted from Bohem at al., 1985.

For a number of relatively large and deep basins (e.g., Puget Sound and Great Lakes main basins), data have been collected to inventory and estimate transport rates of sediment-associated chemicals, and thus to determine chemical residence times. For the main basin of Puget Sound (Figure 2), the estimated average residence time of chemicals in the upper sediment mixed-layer is approximately 10 years. Water residence times were calculated to range from roughly two weeks to 1 year, depending upon the chemical (Boehm et al., 1985). Overall ecosystem recovery in Puget Sound thus appeared from this analysis to be predominantly a function of sediment residence, which in turn was controlled primarily by physical processes such as sediment deposition and upper-layer mixing rates. This information can be critical to the development of appropriate ecosystem recovery and waste management strategies.

For the shallow, more urbanized embayments in Puget Sound which have exhibited the highest sediment chemical concentrations and the greatest potential for biological effects, our understanding of sediment recovery processes has unfortunately been more limited. Some of the difficulty stems from the added complexity of sediment resuspension and erosion in shallow bays which complicates data analysis. Furthermore, because of erosional forces, long-term sediment accumulation in some shallow areas may be negligible, a condition not usually encountered in deep environments. Assessment of sediment transport conditions in these areas generally requires a more comprehensive field study program, as outlined below.

FIELD SAMPLING AND ANALYSIS

In order to examine natural sediment recovery characteristics in shallow embayments, an integrated program of sediment coring, sediment trap deployment, and monitoring of suspended sediments and currents was conducted. The studies focused on Eagle Harbor and the Seattle waterfront on Elliott Bay (Figure 2). Nearshore sediments in both of these central Puget Sound embayments have a documented potential for biological effects, primarily related to accumulations of polycyclic aromatic hydrocarbons (PAHs).

Sediment coring was conducted using SCUBA techniques at eight locations in Eagle Harbor and at two locations in Elliott Bay waterfront. Sediment traps were also deployed over a 2-month period at three locations in Eagle Harbor and at one location in Elliott Bay. Sediment core and trap samples were analyzed for bulk physical characteristics, naturally occurring radioisotopes (e.g., ^{210}Pb), trace metals, and semivolatile organic contaminants. Suspended sediment and current monitoring was performed as a component of other related programs.

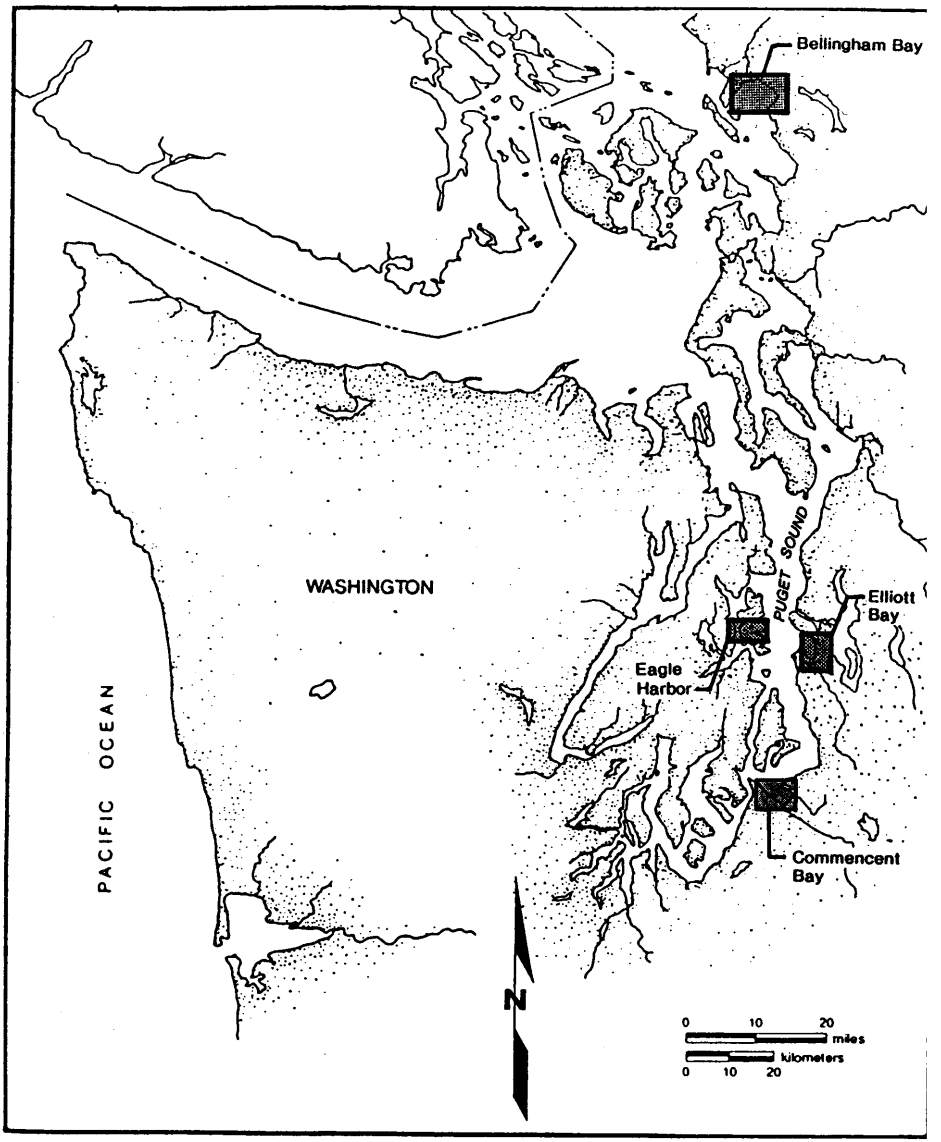

Figure 2.
LOCATION OF STUDY AREAS.

The Eagle Harbor and Elliott Bay investigations were supplemented with other, similar studies performed in the City Waterway of Commencement Bay (Norton, 1990) located in the southern region of Puget Sound (Figure 2). All three of these embayments are currently being addressed under state and federal Superfund cleanup programs. More limited data is also available from nearshore areas of Bellingham Bay in northern Puget Sound (Bothner et al., 1980).

DATA ANALYSIS

Depth variations in the activity of ^{210}Pb, a naturally occurring radioisotope in sediment cores, can be used as a measure of both sediment mixing and burial rates, as long as they occur over a time span comparable to the radioisotope's half-life of 22 years. Typical vertical profiles of ^{210}Pb activity in cores collected from Eagle Harbor and the Elliott Bay waterfront areas are presented in Figure 3a and 3b, respectively. Although these figures resemble in pattern ^{210}Pb profiles observed in deep-water environments (Lavelle et al., 1985), the mechanism(s) contributing to these patterns may not be similar. Considering that all four shallow embayments may exhibit no long-term sedimentation, minimum and maximum burial and mixing rate estimates were calculated for the range of possible sediment deposition scenarios. Methods of ^{210}Pb data analysis used in this evaluation are outlined in Lavelle et al. (1985).

A summary of the net sediment burial rate calculations is presented in Table 1. Net sedimentation rate estimates for Eagle Harbor and the Elliott Bay waterfront ranged from 0 to 0.3 gms/cm^2-yr (equivalent to 0 to 1 cm/yr). These values are considerably smaller than the total deposition rate measured in sediment traps at the same locations, which ranged from 0.8 to 1.8 gms/cm^2-yr. Based on these data, considerable resuspension of sediments is indicated in both Eagle Harbor and Elliott Bay. A somewhat lower resuspension rate is evident in the more protected City Waterway of Commencement Bay.

In the absence of significant currents, much of the sediment resuspended within the water column may simply return to its original sediment location. However, tidally-averaged current velocities in the shallow embayments range between approximately 2 and 4 cm/sec (.04 to .08 knots; with daily maximum velocities generally ten times higher), and are capable of transporting at least a portion of the suspended sediment out of the basins.

In order to determine the quantity of resuspended sediment advected or dispersed out of these nearshore basins, data on local water depths, average current velocities, and particulate settling rates are required (Thomann and DiToro, 1983). Based on the range of measured or calculated values for these parameters, the minimum and maximum rate that resuspended sediments are advected from the basins can be determined. The amount of calculated

Table 1
SUMMARY OF SEDIMENT RESIDENCE TIMES IN SELECTED PUGET SOUND EMBAYMENTS

	Puget Sound Main Basin	Bellingham Bay Urban Region	Elliott Bay Central Waterfront Area	Eagle Harbor	Commencement Bay/City Wtwy
Basin Length (km)	60.0	2.0	8.0	1.3	2.5
Average Basin Depth (m)	110	10	17	7	11
Average Water Column Residence Time (days)	120	0.4	3.0	0.7	1.0
Gross Sedimentation Rate (gms/cm2-yr)	ca 0.8	ca 4.4	0.8	2.0	1.0
Net Sedimentation Rate (gms/cm2-yr)	0.5	0 - 0.8	0 - 0.3	0 - 0.1	0.6
Resuspension-Induced Advection (gms/cm2-yr)	ca 0.01	ca 0.8 - 1.0	0.2	0.2	0.2
Mixed Layer Thickness: (cm)	10	13	10	4	10
Bioturbation Rate in Mixed Layer (cm2/yr)	30	30 - 40	20 - 30	1 - 30	30
Average Surface Sediment Residence Time (yrs)	10	ca 5 - 6	4 - 10	8 - 10	6 - 8

resuspension-induced advection is similar among all three embayments examined, and ranged from approximately 0.1 to 0.3 gms/cm^2-yr (Table 1). These rates are comparable to maximum burial rates, and thus represent a substantial component of overall sediment transport in the shallow embayments.

The remaining component of the sediment transport analysis is vertical mixing within the sediment column. As discussed above, mixing rates were determined from ^{210}Pb analysis in sediment cores, assuming a range of potential sediment deposition scenarios. (In the absence of long-term sedimentation, mixing alone is responsible for chemical movement through the sediment). Following Lavelle et al. (1985), the mixing rates are calculated as Fickian dispersion coefficients, and ranged from approximately 20 to 40 cm^2/yr in all of the embayments studied except Eagle Harbor (Table 1). Calculated mixing rates in Eagle Harbor were generally one-tenth that of the other bays, and ranged from 1 to 3 cm^2/yr. The lower mixing rates in Eagle Harbor appear to be related to a far more cohesive sediment texture characteristic of that bay, which in turn could be related to the more developed polychaete worm community (much of the surface sediment in Eagle Harbor appears to be polychaete fecal material).

Having estimated the various individual components of the sediment transport equation, the residence time of surface sediments within the upper mixed-layer can be calculated as outlined by Thomann and DiToro (1983) and Boehm et al. (1985). For all embayments except Eagle Harbor, the depth of the upper mixed-layer is approximately 10 cm, as determined from ^{210}Pb profiles (e.g., Figure 3b). Consistent with the lower mixing rate, the depth of the upper mixed-layer in Eagle Harbor is approximately 4 cm (Figure 3a). Calculated sediment residence times within the upper mixed-layer of all shallow embayments studied ranged from 5 to 10 years, regardless of whether or not long-term sedimentation was addressed (Table 1).

DISCUSSION

The sediment residence time calculations discussed above and summarized in Table 1 illustrate the dynamic nature of sediment transport in these shallow environments. Approximately every 5 to 10 years, the inventory of surface sediments present in the upper mixed-layer of these embayments is replaced with "new" sediment material, primarily due in this case to resuspension and transport out of the nearshore basins. Chemical concentrations and attendant risks in these areas would thus be expected to respond measurably to changes in the quantity of chemicals released into the embayments. Recovery from prior inputs (e.g., due to previous source controls) may also be reflected in sediment profiles of chemical concentrations, which in some cases can serve to verify the recovery rate predictions.

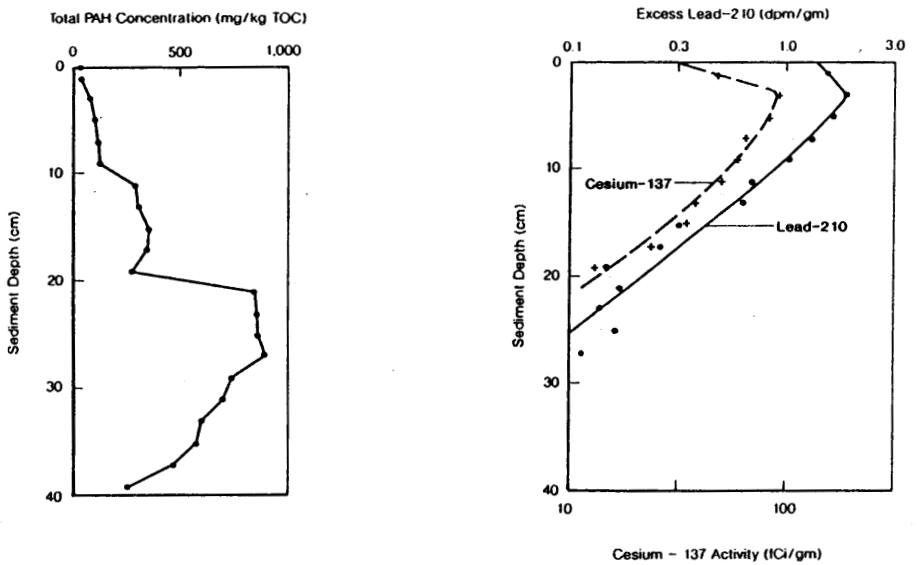

Figure 3A.
PAH AND LEAD-210 PROFILES IN EAGLE HARBOR

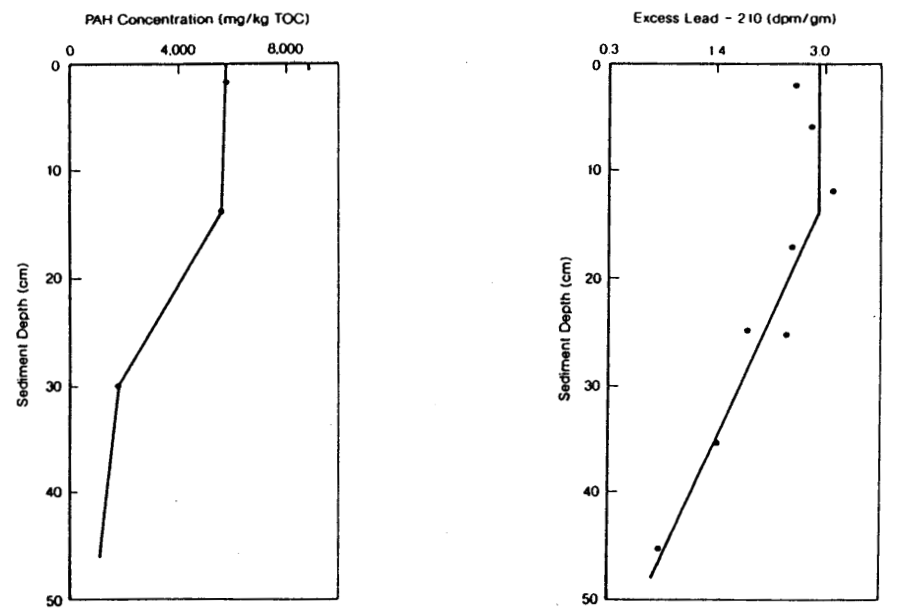

Figure 3B.
PAH AND LEAD-210 PROFILES AT PIER 64/65, ELLIOTT BAY

The sediment residence time results have important implications for the development of appropriate ecosystem recovery and waste management strategies in the nearshore areas. These implications are best illustrated in the examples presented below.

Eagle Harbor — Recovery from Prior Releases

The primary group of chemicals associated with biological effects (or more correctly the potential for effects) in Eagle Harbor are PAHs. A composite profile of total PAH concentrations (normalized to total organic carbon) in the southern region of the harbor closest to a major presumed historical PAH source (prior wood treating operations) is presented in Figure 3a. No major ongoing source of PAH sufficient to result in the observed surface sediment accumulations has been identified. Surface sediment PAH concentrations in this area are also equivalent to those observed in local sediment traps, which is consistent with the resuspension data discussed previously.

A pronounced subsurface maximum in PAH concentrations at a depth of 20 to 30 cm is evident in Eagle Harbor. Although the specific dates of PAH releases are not fully known, the profile is consistent with releases during the first 40 years of operation of the wood treating facility (1900 to 1940), followed by reductions in inputs to the harbor. Based on the coring data, surface PAH concentrations appear to be more than ten times lower today than in the past. A corresponding risk reduction and ecosystem improvement is expected to have occurred.

In addition to sediment transport process, biodegradation likely also contributed to the observed PAH reductions in Eagle Harbor, particularly within the upper oxidized regions of the sediment profile. The role of biodegradation in this case is under continued investigation. In any event, the data demonstrate that further reductions in PAH concentrations over time are expected.

At least for some areas of Eagle Harbor, natural recovery appears to be a viable method of sediment remediation. Isolation or removal of several residual "hot-spots" identified in the harbor would further speed recovery at this site. Under such a scenario, sediment concentration reductions of 50 percent could be expected at least every 5 to 10 years.

Elliott Bay Waterfront — Ongoing Inputs Likely

Like Eagle Harbor, surface sediments in the Seattle waterfront area of nearshore Elliott Bay contain elevated concentrations of PAHs which have the potential to result in biological effects. These sediments are being replaced approximately every 5 to 10 years. However, unlike Eagle Harbor, the highest concentrations of PAHs occur in surface sediments throughout the upper mixed-layer (Figure 3b). Similarly high concentrations were also observed in

local sediment traps. When these data are analyzed in the context of the sediment transport (and potential biodegradation) model discussed above, it is apparent that an ongoing source of PAHs continues to enter this area. Though there are no identified active industrial sources in the vicinity, there are a number of postulated diffuse sources. The source(s) of the PAH releases has not yet been identified.

Although potential environmental risks are currently associated with sediments in the Elliott Bay waterfront, isolation or removal technologies applied to this area are not advisable prior to adequate source controls. Relatively rapid recontamination of this area would likely occur if the source(s) was not controlled, resulting in little net environmental benefit. In this case, an understanding of the processes which control natural recovery can lead to the development of a more comprehensive ecosystem recovery strategy. Given the relatively rapid rate of sediment replacement in this area, a combination of source controls and natural recovery may ultimately provide an effective method of sediment remediation.

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CAPPING OF CONTAMINATED SEDIMENT IN PUGET SOUND

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INTRODUCTION

This paper will address the concerns regarding implementing an effective cap design. Case histories of regional projects will be reviewed (1) to provide insight into why capping is being considered as an alternative to treatment of contaminated sediment, and (2) to identify sites where capping has been applied. This paper will focus on the issues involved in cap design, including site considerations, constructability, and engineering acceptability. A multidisciplinary approach to cap design will also be discussed.

HISTORICAL BACKGROUND

The application of certain capping methods and techniques often has its origins in past projects. The ongoing effectiveness of past capping projects also sets a precedence for their use today. In the Northwest (Puget Sound in particular), capping has been used extensively. By studying past projects and noting their differences and similarities, a range of design alternatives presents itself.

Capping Concept

One of the first capping projects was conducted by the Corp of Engineers with the New England Disposal Area Monitoring System (DAMOS) program in the 1970s. At the New England sites, contaminated material was capped and monitored to assess the effectiveness of the cap in isolating the contaminated sediments from the water column (O'Connor, 1983) (see Table 1). The *in situ* capping of these contaminated sediments provided an environmentally sound, technically feasible and cost-effective approach to containing the problem sediments. Since capping provides a lower cost alternative to other forms of sediment handling (eg., incineration, landfill, nearshore containment), it is increasingly being considered for use in Puget Sound.

Capping, in this context, is the controlled and accurate placement of a clean isolating layer of material over clean or contaminated subaqueous material (sediment). Capping has been used for bottom stabilization (pers. comm. from Bob Lofgren, Riedel International, Portland, Oregon, 1990) and contaminant isolation. Table 1 illustrates selected capping projects in the Northwest, nationally, and internationally.

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These projects have used the following methodologies:

- Contained aquatic disposal (CAD): removal of sediments and placement of the sediments into an existing depression or pre-excavated disposal pit. The Duwamish project (Sumeri, 1989, and Table 1) involved depositing contaminated sediment in a subtidal pit and capping with clean dredge sediment.
- Mounding: level bottom dumping of materials in a discrete mound, followed by capping (such as in the New York Bight project). Mounding is often used in subtidal areas where is it impractical to excavate a pit for containment. Material is dumped in a cohesive mass that forms a mound and is then capped with clean sediments.
- *In situ* capping: emplacement of clean material over in-place contaminated material (Denny CSO project; Romberg, 1987). *In situ* capping is used when it is preferable to contain the sediment in place rather than to remove it.

Effectiveness of Capping

The effectiveness of capping contaminated sediments using various materials of differing thicknesses has been researched in laboratory studies (Brannon, 1985). These studies attempted to simulate the impact of the water column to determine the required thickness of the cap material to prevent diffusion of the contaminant through the cap. Some chemical isolation was found with as little as 5 centimenters (cm) of cap, with the greatest chemical isolation found with a 50 cm cap thickness. However, chemical isolation is only one factor impacting cap effectiveness.

Biological isolation is also a key concern. The cap must be of adequate thickness to prevent burrowing aquatic organisms from reaching the contaminated sediment and should provide a suitable media for their recolonization. Therefore, knowledge of existing biota is a prerequiste to capping. The proposed Navy Homeport project (Palermo, 1989) took into account the thickness of the cap for biological isolation (80 cm), but did not adequately address the impact of disposal of dredge sediment and capping on the marine biota at that site. Various cap thicknesses have been used in Puget Sound projects, ranging from an average thickness of 0.5 meters at the Seattle Ferry Terminal to 3.7 meters at the Simpson Kraft site (see Table 1). So, while an average "effective cap thickness" may have been studied (Brannon et al.,1986), the actual design cap thickness should account for unique site characteristics and project objectives.

Another key issue is cap stability. The thickness of the cap and the material selection have little impact if the cap cannot be kept in place. Therefore, hydraulic conditions at a site should be known. The cap at the Central Long Island Sound experienced little erosion under normal hydraulic conditions, although hurricane storms did cause some erosion (Shields and Montgomery,

1984). Moreover, site conditions such as water depth, slope, bottom sediment stability, the presence of debris, navigational impacts, current discharges, and utilities will impact cap effectiveness.

PROJECT OBJECTIVES

The project objective and site considerations often determine the most suitable capping method. For example, at the Central Long Island Sound Disposal Area, contaminated material had been deposited in a mound on the seafloor, while the material from the Duwamish project was deposited in a pit.

The Central Long Island site was being used for dredge material disposal. There, material could be quickly deposited in mounds without concern for navigational impacts. At the Duwamish site, removal of contaminated material was required so that shipping in that waterway would not be limited (Sumeri, 1986). A nearby subaqueous pit was selected for the Duwamish project to contain the sediment and cap without causing navigational restrictions.

Whether the contaminated sediment has to be removed because of navigational and development concerns (One Tree Marina) or environmental impacts, the removal of the contaminated sediment definitely impacts the selection of a capping option.

Contained Aquatic Disposal vs *In Situ* Capping

When contained aquatic disposal (CAD) is being evaluated as a remediation alternative, its advantages over *in situ* capping should be determined. In a feasibility study for contaminated sediment in Eagle Harbor (CH2M Hill, 1990), *in situ* capping and CAD were both evaluated as remediation alternatives. Because of the range of site conditions, both alternatives could be applied to the site.

However, the advantages of CAD over *in situ* capping should be compared with the impacts of dredging the contaminated material. While the CAD concept results in an engineered, consolidated disposal site for sediments with limited topographic impacts, the removal and subsequent disposal of contaminated sediment has a greater environmental impact than *in situ* capping. *In situ* capping poses less apparent short-term environmental risk than CAD because the contaminated sediment is not removed. Therefore, in cases where contaminated material does not have to be removed, *in situ* capping has been the selected alternative. This has been demonstrated in recent Puget Sound projects where *in situ* capping was used, such as at Simpson Kraft, the Seattle Ferry Terminal, and Denny CSO.

Precedence Setting For *In Situ* Capping

Capping in high energy intertidal areas has not been done in the Puget Sound area, although *in situ* capping of intertidal sediments is being evaluated in Eagle Harbor and Lake Union. The impacts of ferry and boat traffic, wave energy, steep slopes, and public access are unique concerns to intertidal capping. The success of the Portland General Electric (PGE) project will set precedence for capping of high-energy intertidal zones. This project will help to determine the feasibility of capping in high energy intertidal zones both in Puget Sound and nationwide.

CASE HISTORY

The PGE Station L site is located on the eastern shore of the Willamette River in Portland, Oregon. PGE operated a steam-powered electricity plant at the 28-acre site. Historical records showed that a transformer at the turbine building along the shoreline failed, releasing PCBs into the water. Riverbed sediments along the shoreline (an area of approximately 80 by 120 feet) of the PGE Station L site were contaminated.

After studying alternatives to contain, treat, and dispose of the contaminated sediment (CH2M Hill, 1989), a remedial action was selected and outlined in a record of decision. The selected alternative consisted of low-volume dredging to remove surface-contaminated sediment followed by capping the site to prevent further exposure.

A dive survey of the site helped to identify site conditions that impacted the dredging and cap design. A large amount of subsurface debris coupled with steep slopes and existing structures restricted dredging and cap placement. Moreover, there was concern that the removal of the debris would disperse the contaminated sediments. Low-volume dredging was implemented so that (1) existing debris could be worked around, and (2) disturbance of debris would be minimal. Since this method would not completley remove all of the contaminated sediment under the debris, a cap was also required.

Cap Design

The cap needed to be designed for chemical and biological isolation as well as stability. Because of the shoreline location and adjacent boat traffic, the impacts of commercial and recreational boating were key factors. (At sites such as Eagle Harbor, intertidal areas, and shoreline sites in Lake Union, the use of armor material to stabilize the cap is being evaluated). Engineering analysis showed that the cap would require armoring to prevent scour.

The steep slopes were also a factor affecting cap placement. With slopes of 1.4 horizontal to 1 vertical, keeping the sand cap in place was a primary concern.

A subaqueous gravel berm was constructed around the perimeter of the site to hold the toe in place and provide a turbidity barrier prior to the placement of the cap material. During construction, the berm proved to be effective for both stabilization and turbidity control.

After the berm was in place, a 0.9 meter (3 ft) (minimum) layer of clean dredge sand was placed with a clamshell dredge. The discharge was carefully controlled, and placement crews began working offshore to inshore and upstream to downstream to limit turbidity and movement of the sand layer. Low-flow river conditions also aided in the placement. After taking soundings to measure the thickness of the sand isolating layer, a protective gravel filter material (4 inch minus) was placed. Rip rap armoring followed the placement of the gravel layer.

Alternatives to conventional rip rap armoring were considered to reduce the overall cap thickness. Concrete revetment matting such as "ARMORFLEX" was evaluated. However, to conform with ongoing shoreline modifications that used rip rap adjacent to the PGE site, rip rap was selected. Since no sediment cores were required for monitoring of chemical isolation, only physical monitoring will be conducted at the PGE site. No provisions for ongoing monitoring of the sand isolating layer through the armoring were implemented. Therefore, the physical stability of the cap is imperative to assure isolation of the contaminated sediment.

CONCLUSIONS

Capping is being evaluated as an effective method of containing contaminated sediment in both the subtidal and intertidal areas. Until recently, most capping projects were in so-called quiescent subtidal areas. Capping in high energy intertidal areas presents unique challenges to assure cap stability and long-term effectiveness. Proposed intertidal capping projects in Puget Sound should include provisions for sampling and monitoring so that long-term effectiveness can be measured.

Table 1
DESCRIPTIONS OF SELECTED CAPPED DISPOSAL PROJECTS: NORTHWEST PROJECTS

PROJECT		CONTAMINATED MATERIAL			CAPPING MATERIAL		
Location (date)	Site Char'cs	Vol. of Material* (m^3)	Dredging Method	Placement Method	Volume* type m^3	Thickness of Cap (m)	Placement Method
Duwamish Waterway, Seatle, WA (1984)	Existing subaqueous depression 12 m deep	840	Clamshell	Scow	2,700	0.3-1.0	Sprinklng from bottom dump scow
One Tree Island, Olympia, WA (1987)	Contained Aquatic Disposal of material 11m deep conical pit	3,000	Clamshell	Scow	3,000 (dredge sand)	1.2 (minimum)	Clamshell
Simpson Tacoma Kraft Co., Tacoma, WA (1988)	Institute capping of 6.9 ha of contaminated near shore area	N/A	N/A	N/A	153,000 (dredge sand)	.6 - 3.7	Hydraulic Dredge with Energy Dissipating Box
Denny Way (CSO), Elliott Bay, WA (1989)	Institute capping of 11,000 mz contaminated near shore area	N/A	N/A	N/A	12,000 (dredged sand)	.9 (Minimum)	sprinkle from bottom dump scow

* All volumes are approximates
--- Indicates volumes are unknown or not reported.

Table 1
DESCRIPTIONS OF SELECTED CAPPED DISPOSAL PROJECTS: NORTHWEST PROJECTS, CONTINUED

PROJECT		CONTAMINATED MATERIAL			CAPPING MATERIAL		
Location (date)	Site Char'cs	Vol. of Material* (m^3)	Dredging Method	Placement Method	Volume* type m^3	Thickness of Cap (m)	Placement Method
Portland General Electric Co, Portland, OR (1990)	Low Volume dredging and capping of 900 m^2 of shoreline sediments with armoring	200	low-volume, hand-held, dredge	upland disposal	5,000; sand gravel, filter, and rip rap	1.8 - 3.6	Clamshell
Seattle Ferry Terminal, Elliott Bay, WA (1989)	In situ capping of 11,600 m^2 contaminated near shore area	N/A	N/A	N/A	6,900 (process sand and quarry spalls)	.5 (Average)	Clamshell

* All volumes are approximates
--- Indicates volumes are unknown or not reported.

Table 1
DESCRIPTIONS OF SELECTED CAPPED DISPOSAL PROJECTS: PROJECTS OUTSIDE OF NORTHWEST

PROJECT		CONTAMINATED MATERIAL			CAPPING MATERIAL		
Location (date)	Site Char'cs	Vol. of Material* (m^3)	Dredging Method	Placement Method	Volume* type m^3	Thickness of Cap (m)	Placement Method
Rotterdam Harbor, The Netherlands (1981-1983)	Phase I: Botlek Harbor excavated to 29.9 m deep	920,000	Trailing suction hopper	Pumpout submerged diffuser	--- (clay)	0.6 - 1.0	Scow, then leveled over site
	Phase II: First petroleum harbor excavated to 24.4 m deep	470,000	Matchbox suction	Pipeline submerged diffuser	--- (clay)	0.6 - 1.0	Scow, then leveled over site
New York Bight (1980)	Generally flat bottom 24.3-27.4 m-deep	660,000 (mounded to 1.8 m thick)	Clamshell	Scow	1,400,000 (majority fine sand)	Average 1-1.2; Maximum 1.5-2.7	Scow, hopper dredge

* All volumes are approximates
--- Indicates volumes are unknown or not reported.

Table 1
DESCRIPTIONS OF SELECTED CAPPED DISPOSAL PROJECTS: PROJECTS OUTSIDE OF NORTHWEST, CONTINUED

PROJECT		CONTAMINATED MATERIAL			CAPPING MATERIAL		
Location (date)	Site Char'cs	Vol. of Material* (m^3)	Dredging Method	Placement Method	Volume* type m^3	Thickness of Cap (m)	Placement Method
Central Long Island Sound Disposal Area (1979)	Stamford-New Haven North: generally flat, bottom 19.8m deep	26,000 (mounded 1 - 1.8 m thick)	Clamshell	Scow	50,000 (sand)	Up to 2.1 - 3.0	Hopper dredge
	Stamford-Hew Haven South: generally flat, bottom 21 m deep	38,000 (mounded 1.2-1.9 m thick)	Clamshell	Scow	76,000 (cohesive silt)	Up to 4.0	Scow
Central Long Island Sound Disposal Area (1981)	Norwalk: generally flat bottom 19.8m deep	70,000 (multiple mounds up to 2.5 - 3.6m thick)	Clamshell	Scow	280,000 (silt and sand)	Up to 1.8 - 2.1	Scow

* All volumes are approximates
--- Indicates volumes are unknown or not reported.

PROJECT		CONTAMINATED MATERIAL			CAPPING MATERIAL		
Location (date)	Site Char'cs	Vol. of Material* (m^3)	Dredging Method	Placement Method	Volume* type m^3	Thickness of Cap (m)	Placement Method
Central Long Island Sound Disposal Area (1983)	Cap Site No. 1: generally flat, 18.3 m deep	25,000 (mounded 1m thick)	Clamshell	Scow	60,000 (silt)	Incomplete coverage	Scow
	Cap Site No. 2 generally flat, 17.0 m deep	30,000 (low mound, 0.6 m thick)	Clamshell	Scow	30,000	Irregular: Maximum 1.4, Minimum 0.2	Scow
Hiroshima Bay Japan (1979-1980)	Contaminated bottom sediment overlaid in situ with capping material 21 m deep	N/A	N/A	N/A	--- (sand with shell)	0.5	Conveyor to gravityfed submerged tremie. Suction/ pumpout through submerged spreader bar
Central Long Island Sound Disposal Area (1982-83)	Mill-Quinnipac: generally flat bottom 19.8m deep	30,000	Clamshell	Scow	990,000 (silt)	Multiple broad area placement; estimated average 1.8 - 3.0	Scow

* All volumes are approximates
--- Indicates volumes are unknown or not reported.

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POST-DISPOSAL MAPPING OF DREDGED MATERIAL IN PORT GARDNER AND ELLIOTT BAY

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INTRODUCTION

Post-disposal monitoring of the Puget Sound Dredged Disposal Analysis (PSDDA) program's Phase I (Central Puget Sound) disposal sites was conducted in 1990 at the Elliott Bay and Port Gardner non-dispersive sites. The objective of this monitoring was to assess the impacts of dredged material disposal at each site by documenting present site conditions and by comparing these conditions to the information collected prior to disposal. This paper presents the results of the PSDDA physical monitoring conducted to determine if disposed sediments remained on-site. The 1990 PSDDA chemical and biological site monitoring results are presented in another paper in these proceedings (Striplin et al., 1991).

During the winter of 1989-90, approximately 130,000 cubic yards (cy) of dredged material were deposited at the Elliott Bay disposal site. Each disposal scow was directed to the center of the site by the U.S. Coast Guard. From October 1989 through mid-March 1990, 990,000 cy of dredged material were deposited at the Port Gardner disposal site. Scows were permitted to open their doors within an 183 meter (600') radius target zone at the center of the site.

An optical sediment vertical profiling system (SVPS) was used at the Port Gardner and Elliott Bay disposal sites as one element of the PSDDA post-disposal monitoring. The primary objective of the sediment-profile surveys was to map the distribution of dredged material on the seafloor. SVPS technology is an innovative seafloor photographic technique developed by scientists at Science Applications International Corporation (SAIC). The technique has been used extensively to map the distribution of disposed dredged material at open-water disposal sites (e.g., see Germano and Rhoads, 1984; SAIC, 1986a, 1986b, 1988, 1990). The 1990 PSDDA SVPS monitoring represents one of the few times that this technology has been used to map the post-disposal distribution of known quantities of dredged material accurately disposed in relatively deep water. Depth at the Elliott Bay and Port Gardner

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sites is 85 and 130 meters (m), respectively. The SVPS results presented here were compared and used to verify U.S. Army Corps of Engineers' numerical models, which are used in estimating the dispersal of disposed dredged material.

METHODS

Sediment-Profile Image Acquisition

SVPS surveys were conducted from 27 to 30 April 1990 at Port Gardner and Elliott Bay, 4-6 weeks following disposal. Fifty sediment-profile stations were occupied in and around the Elliott Bay Disposal Site, and 65 stations were occupied at Port Gardner. The images obtained on the first day at each site were assessed prior to the second day's field operations, and station locations were adjusted to insure that the boundaries of the dredged material deposit were defined adequately. Two sediment-profile images were obtained at each station. A minimum of one image was analyzed from each station. A second image was analyzed from 20% of the stations.

Sediment-profile images were obtained using a Model 3731 sediment-profile camera (Benthos, Inc., North Falmouth, MA). Color slide film (Fujichrome 50D) was used for all images. The sediment- profile camera obtains images of the top 20 cm of sediment in profile (Figure 1). The camera consists of a wedge-shaped prism with a plexiglass faceplate and a back mirror mounted at a 45 degree angle. The mirror reflects the profile of the sediment-water interface up to an Olympus OM-1 35mm camera which is mounted horizontally on top of the prism. The prism is filled with water, and because the sediment photographed is directly against the faceplate, ambient near-bottom turbidity levels do not affect image quality. The bottom edge of the optical prism is a sharpened blade which cuts through the sediment to produce a vertical profile of the bottom.

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. As the camera is lowered, tension on the winch wire keeps the prism in the up position. The support frame contacts the bottom without disturbing the area directly under the prism. Once the camera frame touches the bottom, slack on the winch wire allows the prism to intersect the seafloor vertically. The rate of fall of the optical prism into the bottom is controlled by an adjustable "passive" hydraulic piston. This allows the optical prism to enter the bottom at approximately 6 cm/sec. The slow fall rate minimizes disturbance of the sediment-water interface. The prism is driven several centimeters into the seafloor by the weight of the assembly. A trigger is tripped on impact with the bottom, activating a 13-second time delay on the shutter release; this allows the prism to achieve maximum penetration before a photo is taken. As the

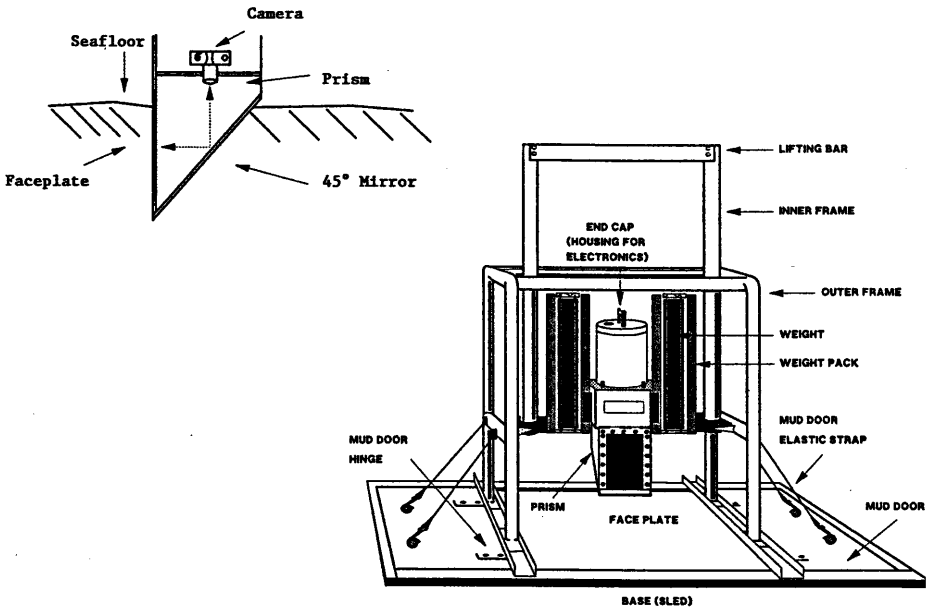

Figure 1.
THE BENTHOS MODEL 3731 SEDIMENT-PROFILE CAMERA.

camera is raised to a height of about ten feet from the bottom, a wiper blade automatically cleans off any sediment adhering to the prism faceplate; the film is advanced by a motor drive, the strobes are recharged, and the camera can be lowered for another replicate image.

Image Analysis

SAIC conducted the PSDDA SVPS surveys using its REMOTS® (Remote Ecological Monitoring Of The Seafloor) system. REMOTS® is a formal and standardized technique for sediment-profile analysis and interpretation. This analysis includes the measurement of up to 21 different physical and biological variables for each sediment-profile image. The details of this interpretive technique can be found in Rhoads and Germano (1982, 1986). The specific image analysis techniques used to map dredged material in Port Gardner and Elliott Bay in 1990 are detailed below.

Dredged material mapping—The ability to detect dredged material in SVPS images is a function of the sedimentary characteristics of the disposed material relative to the characteristics of the ambient seafloor. Dredged material often consists of reduced, fine-grained, sulfidic, organic-rich sediments characteristic of port and harbor environments. This dark gray or black sedimentary material is discernable when it overlies the olive brown or light gray

oxidized surface sediments characteristic of open-water disposal sites. Alternately, disposed dredged material may be apparent in SVPS images because it contrasts in texture with ambient sediments. For example, differences in the grain-size of the dredged material and ambient seafloor may be evident. Moreover, even when disposed sediments are comparable to the ambient seafloor in both texture and optical reflectance characteristics, recently disposed dredged material usually exhibits some feature(s) atypical of the ambient bottom. This may consist of an anomalous "chaotic" or layered fabric, thin apparent RPD depths, or the presence of shell fragments, wood debris, or large, angular mud/clay clasts at the sediment surface.

Imaged dredged material layers may or may not be greater than the camera prism penetration depth. If the entire dredged material layer is evident within the photograph, the distance from the sediment-water interface to the bottom of the layer is measured and mapped. The thinnest layers that can be identified from such images are ca. 1 mm. If dredged material extends below the bottom of the image, then the distance from the sediment-water interface to the bottom of the frame is measured and mapped with a + sign to indicate that the value represents a minimum estimate of the dredged material thickness at that station.

As mentioned above, sediment grain-size can be used to identify dredged material in an image if the disposed material differs from the ambient bottom in this feature. For all images, the grain-size major mode and range are estimated visually from the photographs by overlaying a grain-size comparator which is at the same scale. This comparator was prepared by photographing a series of Udden-Wentworth size classes from silt through granules (≥ 4 phi, 4-3 phi, 3-2 phi, 2-1 phi, 1-0 phi, 0-(-)1 phi, < -1 phi) through the SVPS optical prism in the laboratory. The lower limit of optical resolution of the photographic system is about 62 microns, allowing recognition of grain sizes equal to or greater than coarse silt.

Another feature which can aid in the identification of dredged material in sediment-profile images is the depth of the apparent redox potential discontinuity (RPD) boundary. The apparent RPD marks the bottom of the relatively high reflectance, near-surface sediments evident in the images. In fine-grained sediments, the depth of the apparent RPD is a function of the degree of biogenic sediment mixing (i.e., bioturbation). Following a major benthic disturbance, such as dredged material disposal, apparent RPD depths are shallow. With time and as the benthos recolonize the deposit, the apparent RPD boundary returns to its pre-disposal depth.

RESULTS

The Post Disposal Distribution of Dredged Material in Elliott Bay

Dredged material was detected in images from 17 of the 28 stations sampled within the Elliott Bay disposal site (Figure 2). Dredged material was not detected at any station situated on or beyond the site perimeter located 231 m (1/8 nautical mile) outside the site boundary, nor was it detected at a number of stations situated 100 to 400 m inside of the site boundary. The distribution of dredged material closely mirrors the shape of the disposal site boundary. Material disposed at the site center dispersed farther to the north-northwest (i.e., down the central Elliott Bay trough) than in other directions. The dredged material footprint also extends farther from the site center to the east than to the south or west.

The optical signature of the dredged material in the Elliott Bay images is distinct. The pre-disposal seafloor throughout most of the Elliott Bay disposal site consisted of relatively high reflectance muds with deep apparent RPD layers (i.e., biogenically well-mixed surface sediments), and large feeding voids at depth, produced by head-down deposit feeding infauna (Figure 3). In contrast, the recently disposed dredged material consisted either of extremely low-reflectance (i.e., black), fine-grained sediments and/or poorly sorted fine to medium sands (Figure 4). At six of the central stations, the dredged material thickness is greater than the prism penetration depth (typically 15 cm). These locations are marked with a + sign in Figure 2. The thickness of the dredged material deposit was less than the prism penetration depth at 11 stations which surround this central region. These relatively thin dredged material layers are readily discernible in the sediment-profile images (Figure 5). The distance from the sediment-water interface to the bottom of these layers is mapped in Figure 2.

The Distribution of Dredged Material in Port Gardner

Disposed dredged material was detected in images from 30 stations in and adjacent to the Port Gardner Disposal Site (Figure 6); this includes all stations situated within the disposal site boundary and eight stations beyond the boundary. The latter eight stations are located from 50 to 400 m beyond the disposal site boundary to the north, northwest, west and southwest. Overall, the dredged material footprint was roughly circular, with a radius of approximately 760 m (2500'). The deposit appears to be skewed from the site center to the northwest.

The optical signature of dredged material in the 1990 Port Gardner images is not as distinct as in the Elliott Bay photographs, but the disposed sediments do contrast with the ambient seafloor in several significant ways. Pre-disposal SVPS images, as well as the images collected on the ambient bottom in 1990,

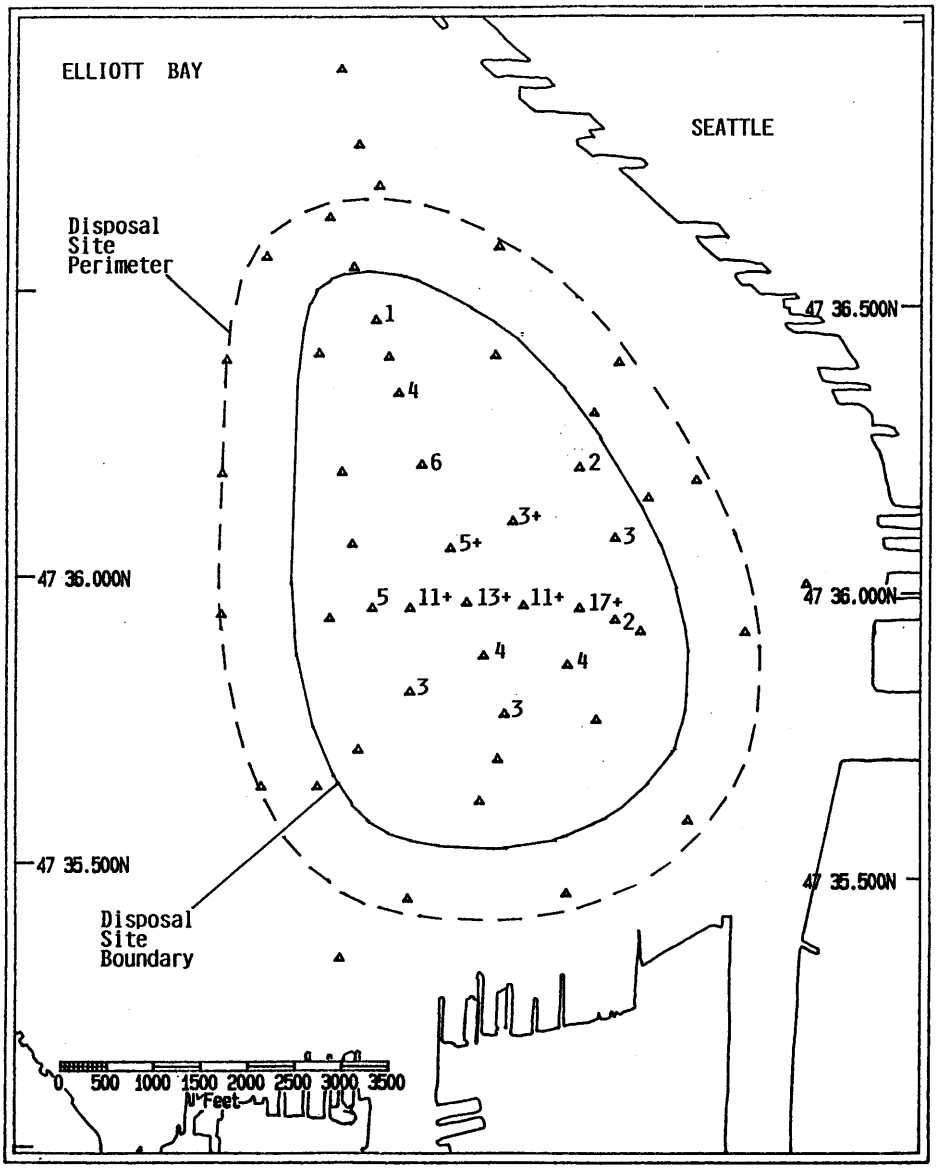

Figure 2.
THE DISTRIBUTION AND THICKNESS (CM) OF DREDGED MATERIAL AT THE ELLIOTT BAY DISPOSAL SITE, APRIL 1990. *Dredged material was not observed at stations (triangles) without assigned values.*

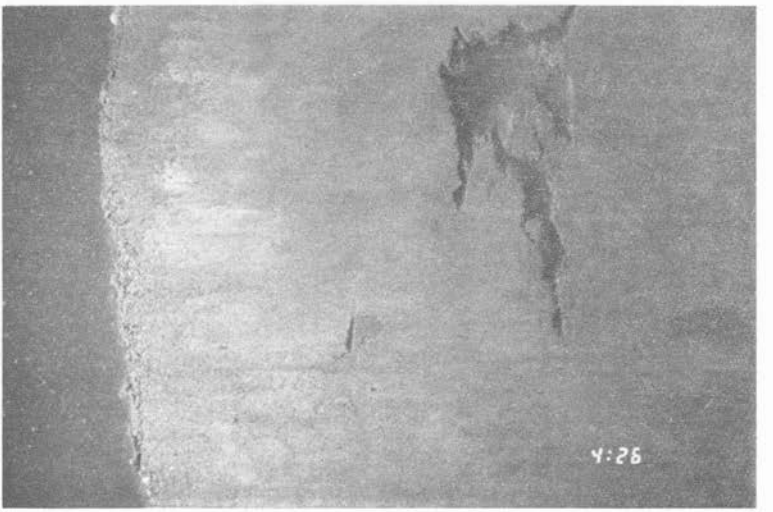

Figure 3.
AN SVPS IMAGE FROM ELLIOTT BAY *showing the ambient bottom which is characterized by high reflectance, well-bioturbated, fine-grained sediments. Feeding pockets of head-down, deposit feeding infauna are evident well below the sediment-water interface. Scale = 0.435X.*

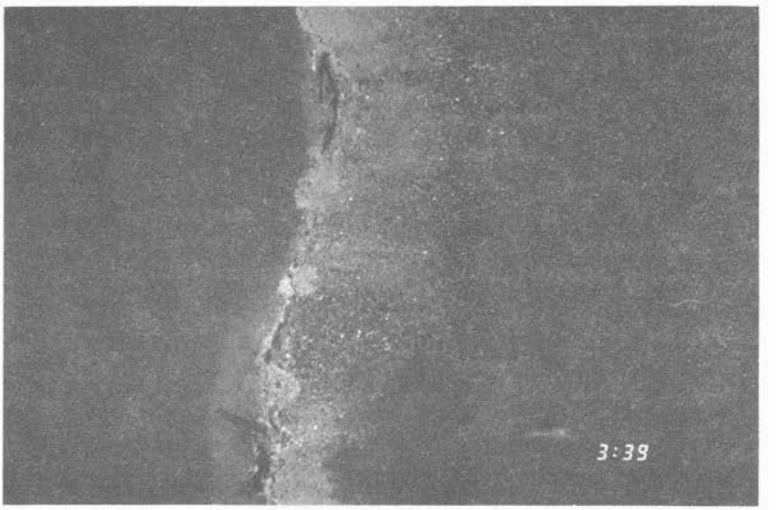

Figure 4.
AN SVPS IMAGE FROM THE CENTER OF THE ELLIOTT BAY DISPOSAL SITE *showing extremely low-reflectance, fine-grained dredged material and disposed sands. Wood debris is also evident at the sediment-water interface. Scale = 0.435X.*

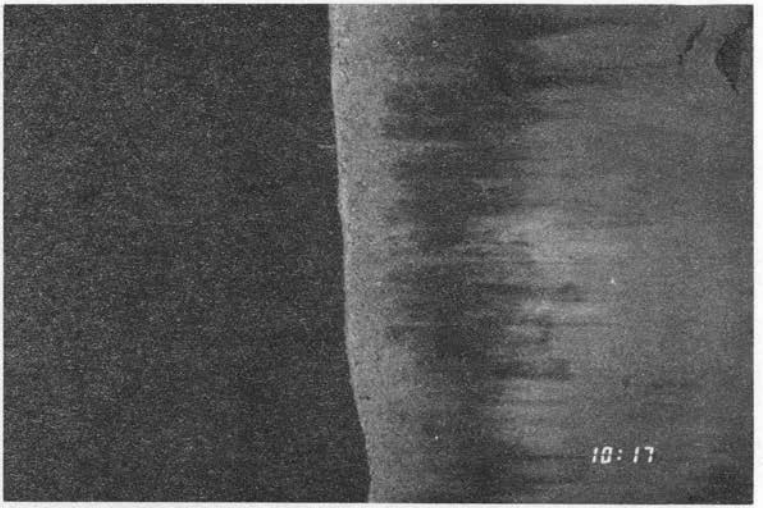

Figure 5.
AN SVPS IMAGE FROM THE FLANKS OF THE ELLIOTT BAY DISPOSAL MOUND
showing a thin (4 cm), low-reflectance, dredged material layer overlying the pre-disposal sediment surface. Scale = 0.435X.

reveal that the Port Gardner disposal site region was characterized by finegrained, biogenically well-mixed sediments (due to ubiquitous head down deposit feeders) with low RPD contrasts (Figure 7). In contrast, the recently deposited dredged material at Port Gardner typically is dominated by very fine sand or a sand/silt mixture. In addition to the grain-size signature, images of the dredged material often show high contrast RPD boundaries and variations in color and/or reflectance from the ambient seafloor (e.g., dark to medium grays versus light grays). Extremely homogeneous or distinctly layered fabrics are also characteristic of the dredged material; these textures are not observed on the biogenically mottled ambient bottom. Some of these dredged material features are illustrated in Figure 8.

At the majority of the stations located on dredged material, the apparent dredged material layers are thicker than the prism penetration depth (values mapped with a + sign in Figure 6). These relatively deep (i.e., ≥ 10 cm) layers overlie most of the disposal site. Dredged material layers less than the prism penetration depth are observed along the margins of the dredged material deposit. While subtle, these layers do exhibit distinct combinations of the features described above.

Port Gardner grain-size data — The distribution of grain-size major modes at Port Gardner stations, as mapped with the SVPS, reveals three broad-scale facies: a roughly circular central region overlying most of the disposal site

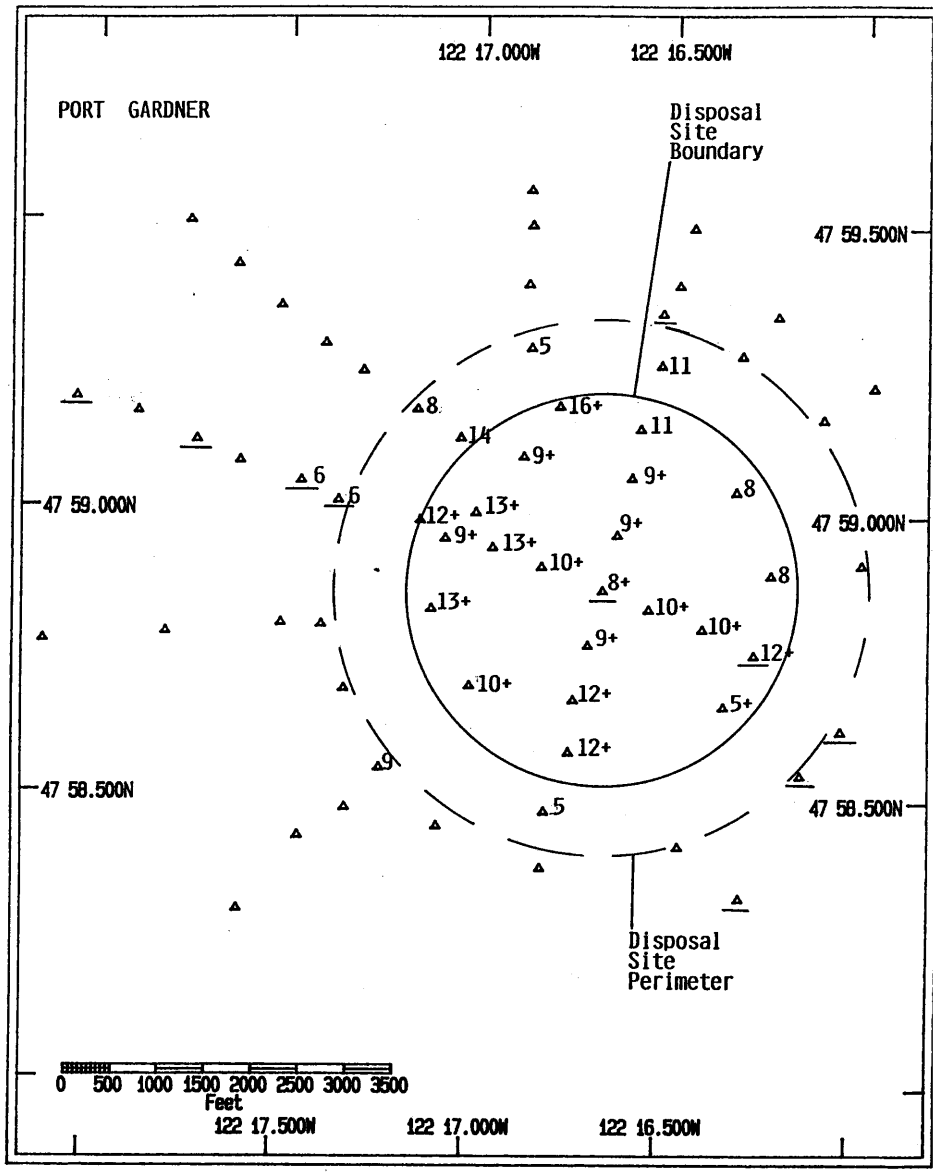

Figure 6.
THE DISTRIBUTION AND THICKNESS (CM) OF DREDGED MATERIAL AT THE PORT GARDNER DISPOSAL SITE, APRIL 1990. *Dredged material was not observed at stations (triangles) without assigned values. Sediment grain-size analyses were conducted at the underlined stations.*

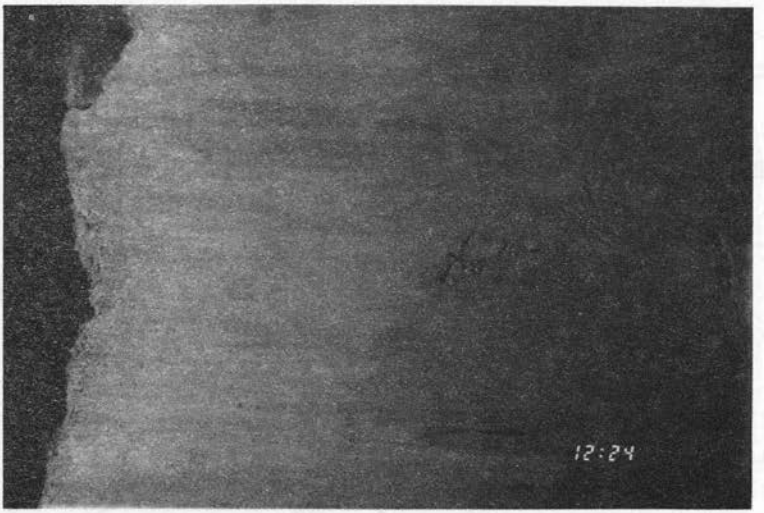

Figure 7.
***AN SVPS IMAGE FROM PORT GARDNER** showing the ambient bottom which is characterized by high reflectance, well-bioturbated, fine-grained sediments. Feeding pockets of head-down, deposit feeding infauna are evident well below the sediment-water interface and small tubicolous polychaete worm tubes are seen at the sediment surface. Scale = 0.435X.*

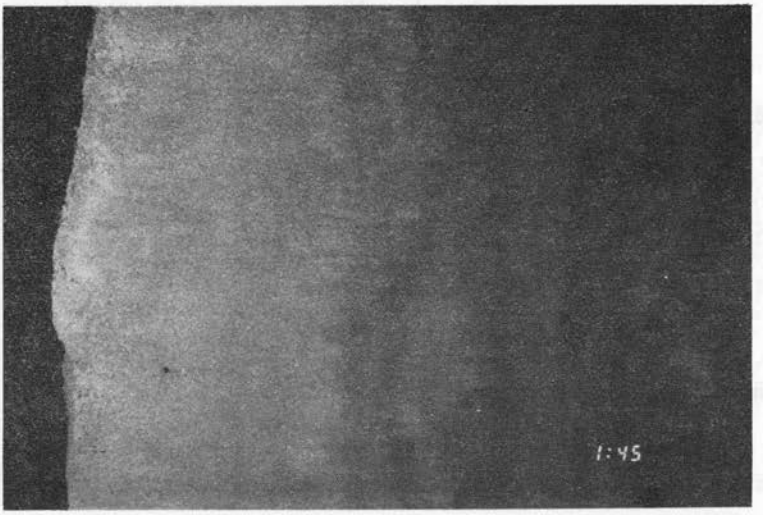

Figure 8.
***A POST-DISPOSAL SVPS IMAGE FROM THE NORTHWESTERN PORTION OF THE PORT GARDNER SITE SHOWING DISPOSED SEDIMENTS.** The diagnostic features of the Port Gardner dredged material include its relative coarseness (compare graininess of this image with Figure 7), the layered, dark bands at depth, and the extremely homogeneous near-surface texture. Scale = 0.435X.*

dominated by very fine sands (4-3 phi), a swath surrounding this area consisting of a mixture of silt-clay and very fine sands (> 4-3 phi), and outlying areas beyond the disposal site perimeter which are predominately fine-grained (≥ 4 phi). During the baseline survey (PTI, 1988), silt and clay sediments (> 4 phi) were predominant across the entire Port Gardner disposal site. The very fine and fine sands reflect the presence of the relatively coarse-grained dredged material. Ground-truth sediment samples analyzed for grain-size at a subset of the SVPS stations corroborate this inference. Comparisons of grain-size data for the 10 stations occupied during both the pre-disposal and the post-disposal surveys (the underlined stations in Figure 6) show the following pattern. At stations within the disposal site boundary (N=2), the sand fraction increased an average of 37%; at stations immediately adjacent to the disposal site perimeter (N = 4), the increase in sand averaged 15%; and at stations well outside the site perimeter (N = 4), the sand fraction increase averaged 6%.

Comparison of the SVPS results to the DIFID numerical disposal model predictions — Using the SVPS mapping results presented here, the Corps of Engineers reevaluated the numerical model that was used to establish the Port Gardner disposal site size during the PSDDA siting process. The results of the numerical modeling using the actual 1989-1990 Port Gardner dredging/disposal operations data (Table 1) are shown in Figure 9. The footprint of the dredged material, as inferred from the SVPS mapping, is superimposed on this figure. The DIFID model predicts a northwest-southeast oriented elliptical deposit which extends just beyond the site boundary along its long axis. The model does not predict the thin layers of dredged material observed well beyond the site boundary to the north, northwest and southwest. Conversely, to the northeast, east, southeast, and south, the modelled dispersion pattern conforms to the SVPS observations. In addition, the model predicts that, except at the extremes of the major dispersal axis, generally thick layers of dredge material (i.e., ≥ 8 cm) will be present along the edge of the mound. This is consistent with the SVPS results which show relatively thick dredged material layers at the periphery of the mound in most directions (see Figure 6; compare with the Elliott Bay results in Figure 2).

ACKNOWLEDGEMENTS

The Washington Department of Natural Resources and the U.S. Army Corps of Engineers (Seattle District) funded this work. These agencies and the Washington Department of Ecology and U.S. Environmental Protection Agency (Region 10) reviewed the manuscript. All results presented here represent information still under review by the PSDDA agencies; the full 1990 PSDDA monitoring findings will be documented in a final report in February 1991.

Table 1.
THE DISPOSAL AND NUMERICAL MODEL DATA USED TO PRODUCE THE SIMULATION SHOWN IN FIGURE 9.

Disposal Data

Clamshell dredge, split hull barge disposal	=	956,000 CY disposed; 581 loads
Average disposal time	=	Approx. 10-90 sec.
Bulk density (GM/CC)	=	1.73
Aggregate Voids Ratio (AVR) at dredged density	=	1.22
Sand concentration by volume	=	0.15 CF/CF
Silt concentration by volume	=	0.29 CF/CF
Clay concentration by volume	=	0.01 CF/CF
Water depth	=	400 feet

Numerical Model Data

Model used	=	DIFID
Simulation time	=	3600 sec.
Current speed	=	10 cm/sec.
Ambient density	=	Constant with depth
AVR immediately after disposal	=	2.93 (from numerical model)
AVR used for thickness calc.	=	2.5 (ie., 25% consolidation)
Deposition calculated for 581 loads @ 1650 CY per load		
Disposal location evenly placed at 9 grid cells in dump zone		
Grid Spacing	=	400 feet

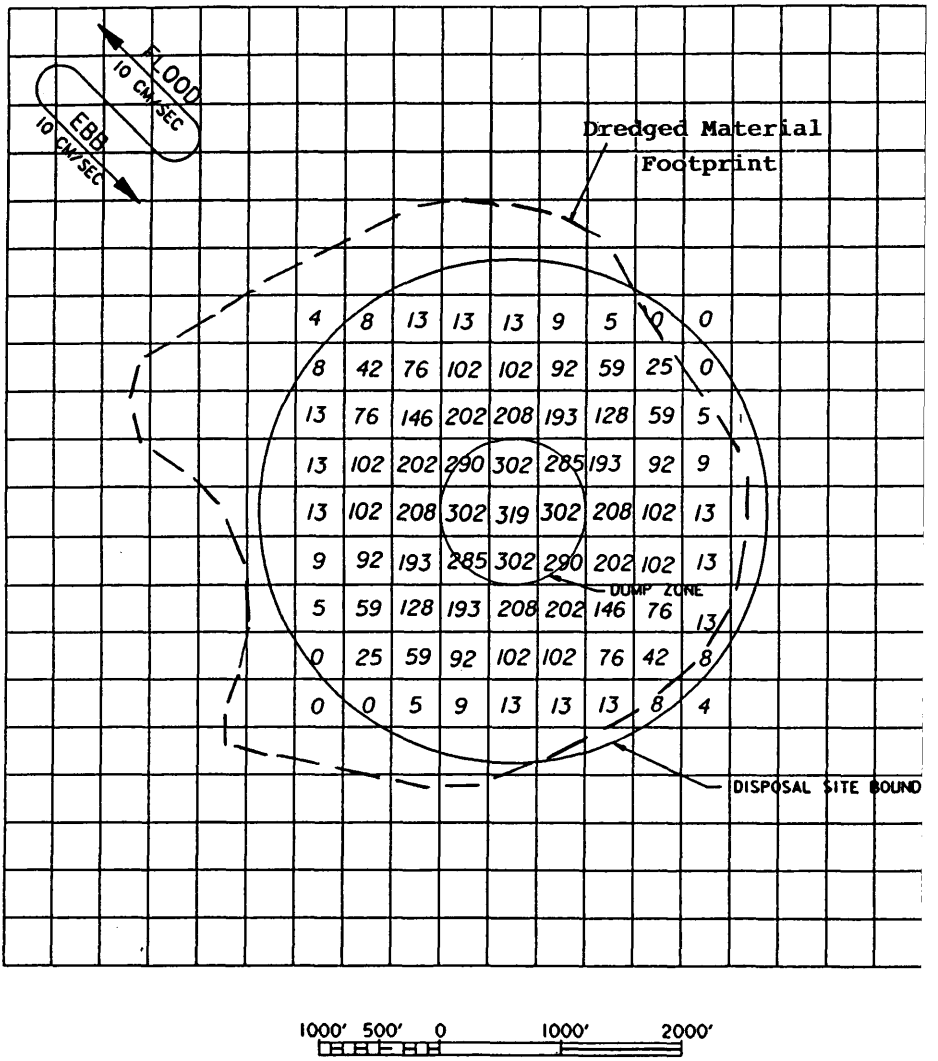

Figure 9.
THE NUMERICAL MODEL'S PREDICTED THICKNESS (CM) OF DREDGED MATERIAL AT PORT GARDNER AFTER 580 DISPOSAL EVENTS. *The disposal and model data used to generate these results are shown in Table 1. The dredged material footprint, as inferred from the SVPS images, is indicated.*

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ENVIRONMENTAL CONDITIONS AT TWO PSDDA OPEN-WATER DISPOSAL SITES: DO THEY MATCH THE PREDICTIONS?

Betsy D. Striplin [1], David R. Kendall [2], and John D. Lunz [3]

INTRODUCTION

The culmination of the multi-year planning effort for the Puget Sound Dredged Disposal Analysis (PSDDA) program was the siting of and obtaining shoreline permits for eight new open-water dredged material disposal sites in Puget Sound. New sediment evaluation procedures were established to ensure that sediments placed at those sites do not cause unacceptable adverse effects to resident biota (site condition II; PSDDA, 1988a). Sediments to be dredged require chemical testing and may require toxicity testing under a tiered sediment evaluation program to determine their suitability for placement at a PSDDA disposal site.

The evaluation criteria for sediments destined for dispersive and non-dispersive disposal sites differ. The criteria are more restrictive for dispersive sites because the dredged material is dispersed over a large area and monitoring for potential effects is not practical. Less restrictive criteria are applied to sediments destined for non-dispersive sites, and those sites receive periodic detailed environmental monitoring based on the volume of dredged material placed at the site. The goal of the environmental monitoring is to assess site conditions and determine whether changes in site management are warranted. Specific objectives of the detailed monitoring are to answer the following questions:

1) Does the deposited dredged material stay on-site?
2) Is the biological effects condition for site management (site condition II) exceeded at the site due to dredged material disposal?
3) Are unacceptable adverse effects occurring to biological resources immediately offsite, due to dredged material disposal?

Through numerical modelling, the size of each disposal site was established such that the material is expected to remain within the site boundary (i.e., the

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answer to question 1 would be "yes"). By approving only those sediments that satisfy the evaluation criteria, it was predicted that the answers to questions 2 and 3 would be "no". In the event that the answer to any of the three questions is contrary to that predicted, then the PSDDA agencies will investigate site management changes.

Baseline site conditions were established for the Port Gardner and Elliott Bay sites during field studies conducted in spring 1988. Baseline data provided the basis for comparisons between pre-disposal (1988) and post-disposal (1990) conditions.

The first post-disposal environmental monitoring at PSDDA disposal sites was conducted in spring 1990 at the Elliott Bay and Port Gardner non-dispersive sites. The Elliott Bay site received 130,000 yds of dredged material from two dredging projects in the Duwamish River, while the Port Gardner site received 990,000 yds, primarily from the U.S. Navy Everett Homeport project (950,000 yds) and secondarily from the Port of Everett Marina project (40,000 yds). Material was placed at both sites during the fall/winter of 1989-1990.

A full monitoring effort, including physical mapping, sediment chemistry, sediment toxicity bioassays, benthic infauna, and bioaccumulation elements, was conducted at the Port Gardner site due to the very large quantity of material placed at the site. Full monitoring enabled answers to be generated for all three questions. The Elliott Bay site was subjected to partial monitoring that included physical mapping and limited sediment chemistry and sediment toxicity bioassays because of the low volume of material placed at the site. Monitoring questions 1 and 2 were answered with the partial monitoring effort.

METHODS FOR 1990 MONITORING

Sample Collection

Samples were collected at a variety of station types. With the exception of physical mapping, which was conducted at all stations, only certain variables were measured at each station type. Onsite stations were located within the disposal site. They were used to assess onsite sediment chemistry and toxicity (question 2). Perimeter stations were situated 1/8 mile outside of the site boundary. Only sediment chemistry analysis was performed at perimeter stations to determine possible offsite movement of dredged material (question 1). Transect stations were placed outside the site boundary in lines running away from the site in down-current directions. Benthic infauna and body burden analyses were performed at transect stations in Port Gardner only to assess potential offsite biological effects (question 3). Finally, benchmark stations were located between the disposal sites and other potential

sources of contaminants. If changes were noted on or near a disposal site, then data from the appropriate benchmark stations were examined to determine whether the changes were confined to the disposal site or whether they were regional and therefore probably not related to the disposal of dredged material.

Physical mapping using a sediment profile camera was initiated in late April 1990 to map the extent of dredged material in and around the two disposal sites. Resulting maps of the dredged material footprint were used to fix station locations for sediment chemical and biological sampling.

Sediment samples were collected in May 1990 from the R/V Kittiwake using a stainless steel 0.1 m^2 double van Veen grab and a 0.06 m^2 Gray O'Hara box core. Sample equipment decontamination procedures and sample collection procedures were in compliance with the Puget Sound Protocols (U.S. EPA, 1986 with revisions). Detailed methods are presented in SAIC (1990).

Laboratory Analyses

Sediments were analyzed for the 58 PSDDA chemicals of concern (PSDDA, 1988a and b) and for conventional variables (e.g., grain size, total organic carbon, total sulfides, ammonia). Analytical methods followed the Puget Sound Protocols (U.S. EPA, 1986 with revisions) with modifications recommended by PSDDA (1990). Acute sediment toxicity was assessed using the amphipod, echinoderm (sea urchin or sand dollar) larvae, and Microtox bioassay tests. Benthic infauna abundance and sea cucumber (*Molpadia intermedia*) body burden methods followed the Puget Sound Protocols (U.S. EPA, 1986 with revisions).

Data Evaluation

Guidelines for data evaluation were developed during the PSDDA planning effort (PSDDA, 1988b). Exceeding the guideline values may lead to additional data evaluation, testing, or site management changes. Guideline values include the following:

- Physical mapping — 3 cm of dredged material at a perimeter station.
- Sediment chemistry — The following guidelines are modified from PSDDA (1988b), and remain under review pending formal adoption: Concentrations of metals and organic compounds at perimeter stations must remain below 1.69 and 2.2 times the baseline concentration, respectively, with those values weighted to reflect spatial uncertainty (see SAIC, 1990).
- Sediment toxicity — Significant toxicity as defined in PSDDA (1988a).

- Benthic abundance—A decrease of 50 percent in the abundances of major taxa relative to baseline abundances.
- Body burden — An increase in the concentrations of metals or organic compounds that is at least two or five times, respectively, the baseline concentration.

RESULTS OF 1990 MONITORING

Elliott Bay

Photographs taken with the sediment profile camera revealed the presence of dredged material well within the disposal site boundary.

Metals were detected at the four perimeter and one onsite station, as were all of the high molecular weight polycyclic aromatic hydrocarbons (HPAHs) and polychlorinated biphenyls (PCBs). Pesticides, low molecular weight PAHs, and some phthalate esters were found in some of the samples. The presence of these chemicals was not surprising, given the number of potential contaminant sources in the vicinity of the site. Field triplicate samples were collected at the onsite station and at two perimeter stations. Chemical concentrations among triplicates exhibited a range that was up to 2-4 times the lowest concentration, indicating substantial spatial patchiness in chemical concentrations.

There were eleven instances when chemical concentrations exceeded guideline values, involving four stations and six chemicals. In each of the eleven cases, the baseline value and/or the 1990 monitoring value was qualified due to their very low concentrations. When taken together, the presence of significant spatial patchiness and qualified chemical data made it impossible to conclude that site condition II had been violated on the site, or that elevated chemical concentrations off the site resulted from dredged material.

Sediments on the disposal site produced some toxicity in the echinoderm larvae test; however, the response did not exceed guideline levels. An elevated ammonia concentration at that station may have caused the observed toxicity. Neither the amphipod nor Microtox tests indicated toxicity on the disposal site.

Because the physical, chemical, and toxicological guidelines were not exceeded at the Elliott Bay site, the PSDDA agencies did not recommend changes to site management.

Port Gardner

The physical mapping studies determined that dredged material exceeded the Port Gardner disposal site boundary. The guideline of 3 cm dredged material at perimeter stations was exceeded at several stations on the western side of the disposal site. Further discussion of these results is found in another paper in these proceedings (Revelas, 1991).

Metals were detected at all onsite and perimeter stations and organic compounds were detected at 12 of 15 stations. There were eight instances of chemicals exceeding guideline values at the Port Gardner site, involving five stations and three chemicals. Bis(2-ethylhexyl)phthlate, a common laboratory contaminant, exceeded its guideline value three times. For the other chemicals that exceeded guideline values (i.e., silver and antimony), both the baseline and monitoring data were qualified. Field triplicate data from Port Gardner onsite and perimeter stations indicated that spatial patchiness resulted in up to 3-fold differences in chemical concentrations at a given station. As occurred for Elliott Bay, the data did not support a conclusion that site condition II had been violated.

Sediments on the Port Gardner disposal site did not exhibit significant toxicity as measured using the amphipod, echinoderm larvae, and Microtox bioassays. Amphipod and echinoderm results indicated that one benchmark station contained toxic sediments.

The abundances of major taxa of benthic infauna at the three transect stations were generally lower in 1990 than during the baseline study. The guideline of a 50 percent reduction in the abundance of major taxa was exceeded at least once at each station and triggered an evaluation of the benthic infauna at one of the benchmark stations (the second benchmark station was not evaluated because it exhibited significant toxicity). Abundances of the major taxa at the benchmark station were comparably lower in 1990, suggesting that the lower abundances at the transect stations were the result of regional events (e.g., poor larval recruitment) rather than the disposal of dredged material. That the species composition of the benthic communities in 1988 and 1990 were similar further indicated a regional change, rather than an alteration caused by dredged material that would most likely result in a change in community composition.

Benthic body burden analyses using the sea cucumber *Molpadia intermedia* failed to show the accumulation of organic compounds at the three transect stations. However, metals were detected in all samples. Although guideline values for metals were exceeded at all stations, the ability to defensibly interpret these data was compromised because information on organism size, which has been shown to positively correlate with the accumulation of metals in many taxa (Boyden, 1977), is lacking.

A preliminary site management change was instituted at the Port Gardner site due to the movement of dredged material offsite. In the future, barges will be required to position at the center of the site during disposal instead of depositing dredged material equally in each of the site's four quarters, as occurred during the Navy project.

SEDIMENT LOADING VERSUS ONSITE SEDIMENT CONCENTRATIONS

The guidelines to evaluate sediment quality at proposed dredging sites were developed to ensure that dredged material placed at the disposal sites does not result in unacceptable sediment contamination. Because it is feasible only to test a fraction of the sediment that is destined for the disposal site, each sample represents a specific volume of material. The remainder of that volume is assumed to contain comparable chemical concentrations. If this is true, then the chemical concentrations observed on the disposal site should approximate the concentrations at the dredging sites.

The average chemical loads of the sediments placed at the Port Gardner and Elliott Bay disposal sites were calculated using volume, total solids, bulk density, and chemical concentration measurements. The loadings were then compared with the ranges of concentrations observed in sediments collected and believed to be dredged material at each disposal site. For both sites, the loadings approximated the onsite concentrations, although more so at the Port Gardner site (Table 1) which is not influenced by other (i.e., non-dredged material) sources of potential chemical contamination.

DO THE RESULTS MATCH THE PREDICTIONS?

With the exception of dredged material outside the Port Gardner disposal site boundary, results of the first year of monitoring at PSDDA disposal sites confirmed the predictions made during the PSDDA planning process. Confirmation is noted in two different ways. First, the two monitoring questions that could be answered with the partial monitoring program in Elliott Bay (questions 1 and 2) were answered as expected, i.e., dredged material stayed onsite, and site condition II was not exceeded on the site. All three questions were answered for the Port Gardner site via the full monitoring program. Although dredged material moved offsite, site condition II was not exceeded on the site and biological effects were not observed off the site. These results indicate that the chemical and biological evaluation criteria applied to sediments proposed for dredging are successfully maintaining sediment quality at the disposal sites.

Table 1.
COMPARISON OF SEDIMENT LOADING CONCENTRATIONS AND ONSITE SEDIMENT CONCENTRATIONS OF CHEMICALS DETECTED AT THE PORT GARDNER DISPOSAL SITE.[1,2]

CHEMICAL	CALCULATED LOADING	ONSITE CONCENTRATION RANGE[3]
Antimony	0.2	1.1E-1.2E
Arsenic	6.7	6.7E-8.2E
Cadmium	0.13	0.15-0.27
Copper	38	27-46
Lead	5.4	2.4U-7.3
Mercury	0.05	0.05E-0.11
Nickel	45	34-50
Silver	0.11	0.11E-0.56E
Zinc	63	72-99
Naphthalene	26	24U-40E
Fluorene	25	22U-25E
Phenanthrene	32	21U-27E
Fluoranthene	37	24U-70
Pyrene	60	24U-97
Benzo(a)anthracene	34	22U-70
Chrysene	39	22U-93
Benzofluoranthenes	45	22U-99
Benzo(a)pyrene	34	22U-70
Benzo(g,h,i)perylene	28	22U-34E
Indeno(1,2,3-c,d)pyrene	27	22U-32E
Bis(2-ethylhexyl)-phthlate	29	25E-89

[1] Metals reported in mg/kg dry weight; organic compounds reported in ug/kg dry weight.
[2] Only detected chemicals are tabulated.
[3] E = estimated value; U = undetected at the concentration shown.

Second, the similarity between sediment loading concentrations and observed sediment concentrations on the disposal sites demonstrates that the sampling requirements at the dredging site (i.e., the numbers of samples and analyses per unit of dredged material) have adequately characterized those sites.

ACKNOWLEDGEMENTS

The Contract Officer for the 1990 monitoring program was Betsy Striplin, Department of Natural Resources. Technical assistance was provided by David Kendall, U.S. Army Corps of Engineers. The monitoring program was conducted by Science Applications International Corporation under the management of John Lunz. David Fox, U.S. Army Corps of Engineers, performed the sediment loading calculations.

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ELLIOTT BAY RENTON EFFLUENT OUTFALL SEDIMENT DATA ANALYSIS

Ralph Domenowske and Nian She[1]

INTRODUCTION

Bacteria, organic and heavy metal data were collected from twenty sediment stations in Elliott Bay (Figure 1) over a six year period starting in 1985. This sampling program was started two years before the 600 foot deep Renton secondary effluent outfall went into service. The bacterium *Clostridium perfringens* was chosen as a "red flag" indicator for this new effluent discharge because its spore form resists chlorination, persists in the environment, and its human origin relates it to sewage discharges. If *C. perfringens* counts increased, Metro proposed expanding the monitoring parameters to identify possible negative impacts such as increases in priority pollutants to the area. Bacterial levels did increase and subsequent monitoring of priority pollutants have identified improvements in these offshore sediments. These improvements are probably due to the diminished use of the nearby Fourmile Rock Dredge Disposal site.

STUDY DESIGN

Location

The Renton Treatment Plant effluent is discharged via an Effluent Transfer System into 600 feet of water in outer Elliott Bay. In March of 1987 this system transferred the Renton effluent discharge from the Green Duwamish River (that flows into Elliott Bay) to the offshore waters of Central Puget Sound. The secondary treated and chlorinated sewage has nearly 12 miles of additional chlorine contact time in the Effluent Transfer System between Renton and Elliott Bay. Two parallel 10,000 foot outfalls each have a 500 foot diffuser section approximately due west from the south shoreline promontory, Duwamish Head. This is the deepest municipal outfall in the world. The discharged effluent remains trapped below 300 feet by the overlying less dense surface waters. This outfall design and location were chosen to eliminate the possibility of human contact, contact with sensitive nearshore habitants, and subsurface currents that would carry the effluent back into Elliott Bay.

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MONITORING PARAMETERS

The NPDES environmental monitoring program for receiving waters was based on three bacterial parameters: fecal coliform and Enterococcus in the water column at five stations, and *Clostridium perfringens* from twenty sediment stations (Figure 1). The water column bacterial data taken from multiple depths around the outfall, is not included in this report; however, that data has remained at background levels since prior to the Renton Treatment Plant discharge. The twenty offshore sediment stations were chosen that best represent the potential effluent discharge impact areas of Elliott Bay and adjoining waters. Those stations are based on extensive modeling and environmental data analysis conducted during the BASELINE planning studies for the Renton outfall.

SAMPLING PROGRAM DESIGN

Data collection for this analysis began in 1985 and continued through the March 1987 start up of the Renton effluent discharges to the present. The water

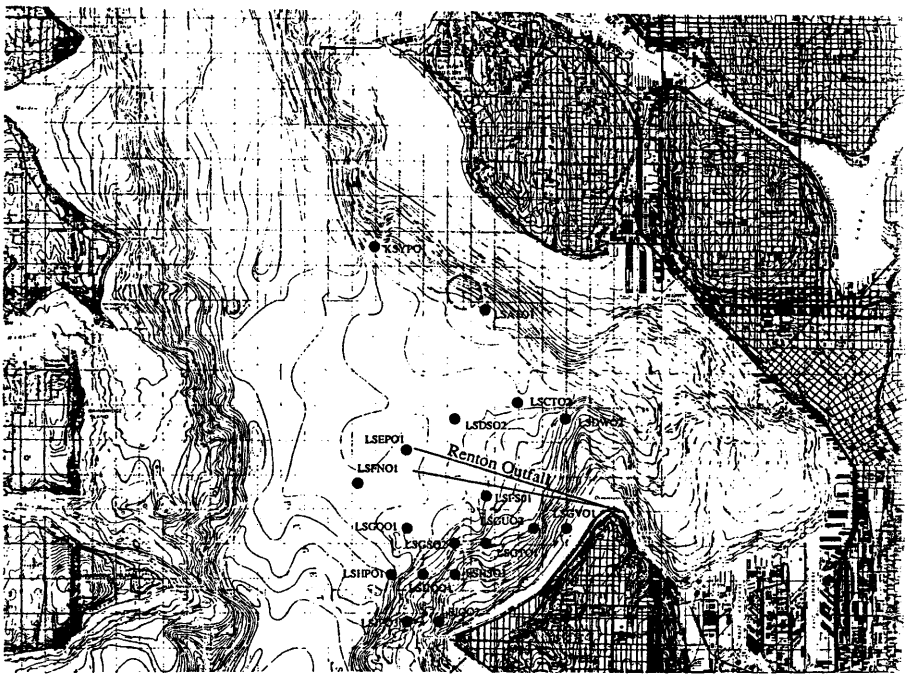

Figure 1.
RENTON OUTFALL SEDIMENT STATION TOPOGRAPHY.

column sampling plan was designed to sample both the trapped effluent field and ambient surface waters.

The majority of the twenty sediment stations in outer Elliott Bay are at the depths where the effluent field makes contact with the seafloor (80% of the time between a 400 to 500 foot depth), and at the greater depths (500 to 630 foot depths) where particle fallout could be expected to occur near the outfall. For the sake of the statistical analysis in this report, the area of the bottom where the trapped dispersed effluent field should encounter the bottom has been referred to as the "seafloor contact zone." The area of the bottom nearest the outfall of equal or greater depths is referred to as the potential "impact zone," based on the concept that effluent particles from the discharge should settle out much like a cloud from a smoke stack might drop particles to the land below. The "seafloor contact zone" and the "impact zone" are used to characterize the two most probable mechanisms that would allow contaminants from the effluent to influence bottom sediments.

STATISTICAL ANALYSIS

The goals of the statistical analysis were as follows:

1. Identify those environmental parameters which have statistically reliable data.
2. Characterize the data for each parameter in a historical sequence that would reliably reflect any changes with time.
3. Identify any spatial relationships between each parameter and known sources.

The statistical procedure used for the *C. perfringens* data is the "bootstrap" method which enables us to assess statistical accuracy of the parameters estimated from the data. It is a computer based method (also called Monte Carlo sampling), which uses a computerized random sampling generator to resample the actual data. It has been shown that as the bootstrap sampling size increases, its standard deviation will approach the actual value for the entire population. The bootstrap method works well when the original samples provide an unbiased view of the entire population. This method is independent of the type of sample distribution (normal, exponential, Chi-squared, etc.).

The spatial relationships were tested using the bootstrap method. We divided the area of interest according to the proximity of the individual stations to the outfall. The impact zone based on proximity, particle "impact zone," and the "sea floor contact zone" were tested using the null hypothesis that there were no differences between regions.

Isobar graphs were drawn which provide graphic evidence that the historic sources for several heavy metals could be attributed to the Fourmile Rock Dredge Disposal Site. The historic decreases in those metals with time coincided with the phase-out of the dredge disposal site for contaminated sediments.

The Bernoulli model and the maximum likelihood estimate were used to estimate the probabilities of detecting all possible organic compounds. The organic priority pollutants was based on enumeration of variations in occurrence of organic compounds. This approach simplifies a very complex data set, based on the premise that if a factor is influencing the environment it will influence more that just the concentration of a few compounds. If all of the 80 tested compounds were found, the probability value would equal one. The levels above and below the detection limits were not distinguished as different, since this test is only intended to indicate the presence or absence of organic compounds. The levels below the detection limits represent valid identifications; however, they are too low to be quantified.

RESULTS

Clostridium perfringens levels are highly variable; however, when the sample size is increased from 20 to 1000 per year through the statistical bootstrap method, these levels have increased in the deep water sediments from throughout the area sampled (Figure 2). The confidence interval from the 1988 and 1989 data in Figure 2 is wider than previous data and may reflect problems in the analytical procedure. This conclusion is based on the 1990 data which were sampled twice and for which both sample variability and magnitude were consistent and reproducible. However all of the post-discharge *C. perfringens* values are statistically higher than the initial pre-discharge data. The geometric mean values successively increase from 1,669 counts per 100 ml in 1985 to 57,134 counts per 100 ml, in 1989, and back down to 24,943 counts per 100 ml in 1990. There was no confidence interval overlap between the 1989 data and any other year besides 1988. This lack of overlap in the 1989 data confidence intervals suggested either a unique environmental change occurred, or the data analysis may be suspect. Since there were no known changes in the input of *Clostridium perfringens* to the environment, the possibility of analytical error was hypothesized. In 1990 the sediment samples were run once in August and again in November, with mean counts of 24,943 and 23,496 per 100 ml respectively. The second 1990 data set reproduced resulted from the first with less than 11 % differences in geometric means.

A Bernoulli model for the priority pollutants based on the frequency of detection over a five year period was developed for the twenty offshore sediment stations. The priority pollutant organics have declined in frequency of occurrence with almost no overlap when the 1985 and 1986 averages are

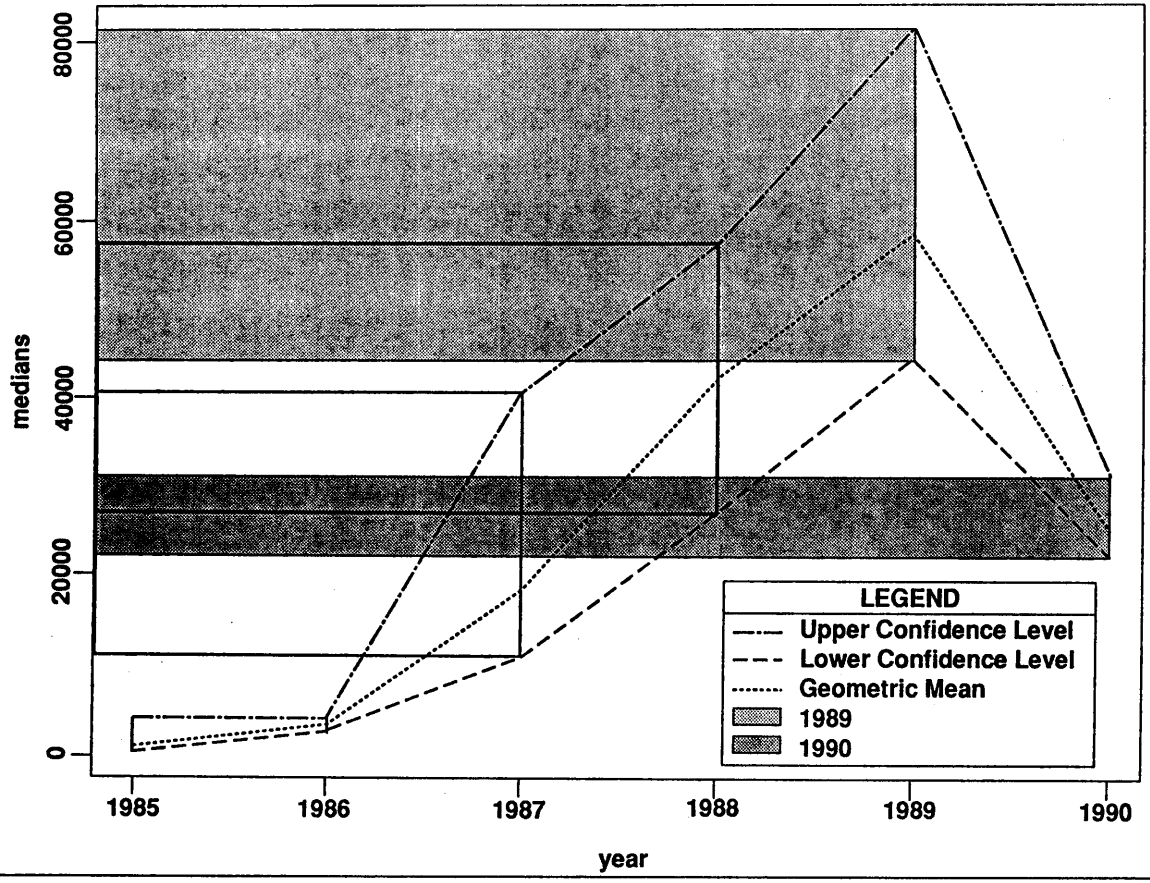

Figure 2.
BOOTSTRAP GEOMETRIC MEAN CLOSTRIDIUM PERFRINGENS COUNTS/100 ML IN SEDIMENTS.

compared to the 1988, 1989 and 1990 data in Figure 3. Of the one hundred and eleven organic priority pollutants, fewer than a dozen were found at detectable levels on a consistent basis. The eleven organic priority pollutants found in "consistently measurable" qualities were benzo(b)fluo, benzo(a)pyrene, benzo(a)anthracene, anthracene, chrysene, benzylbutylphthalate, benzo(k)fluoranthene, pyrene, indeno(1,2,3-c,d)pyrene, benzo(g,h,i)perylene, and fluoranthene. The sediment concentration levels of these priority pollutants are all below the currently proposed sediment standard criteria under review by the Washington State Department of Ecology. None of the organics are ones which could be considered unique to a sewage discharge. There was no relationship in concentrations of priority pollutants with distance from the outfall, based on either the predicted effluent plume "impact zone" or the "seafloor contact zone."

Of the thirteen priority pollutant heavy metals analyzed from these sediments, the seven most predominate in order of their concentrations were zinc, copper, lead, chromium, nickel, silver, and mercury. These heavy metals have either declined or statistically have not increased during the 1985 to 1989 time period. Four of those metals declined in concentration with increasing distance from the Fourmile Rock Dredge Disposal site, as illustrated for zinc in Figure 4. The chromium, nickel, and silver, while in highest concentrations in the immediate area of the Renton outfall, as illustrated for chromium in Figure 5, have also been declining during the period of effluent discharge. The only metal which has not declined with time is mercury, which is distributed with the highest concentrations at the Fourmile Rock Dredge Disposal Site.

CONCLUSIONS

The Fourmile Rock Dredge Disposal Site began to be phased out for contaminated sediments in 1985 and was used for clean sediments after 1987. The apparent decline in metal concentrations with time and distance from the dredge disposal site support the hypothesis that the predominant source of metal contamination to the deep outer basin of Elliott Bay is the Four Mile Dredge Disposal Site. The obvious decline in frequency of occurrence for the priority pollutants from these deep water sediments reinforce this conclusion. It is improbable that the Renton effluent discharge could have played any role in the reduction of either the metals or trace organic concentrations with time. Laboratory quality control and quality assurance programs for these specific tests were examined and no plausible explanation that might account for recording lower values in 1989 over the 1985 and 1986 period could be identified.

The levels of nearly all of the organic priority pollutants and heavy metals have nearly all declined in concentration or frequency of occurrence during the sampling period which began two years before the treatment plant started

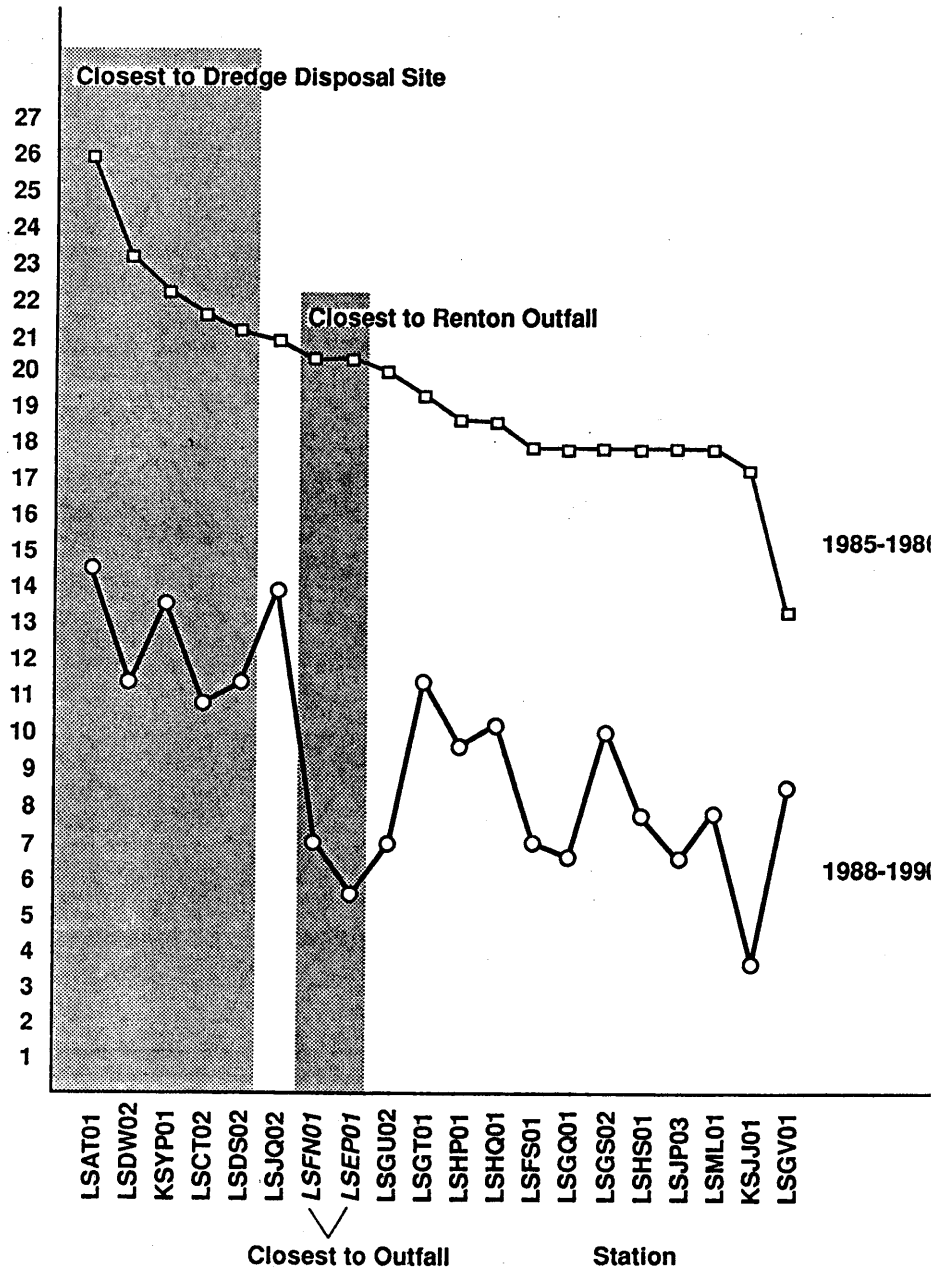

Figure 3.
FREQUENCY OF DETECTION FOR PRIORITY POLLUTANT ORGANICS BY STATION.

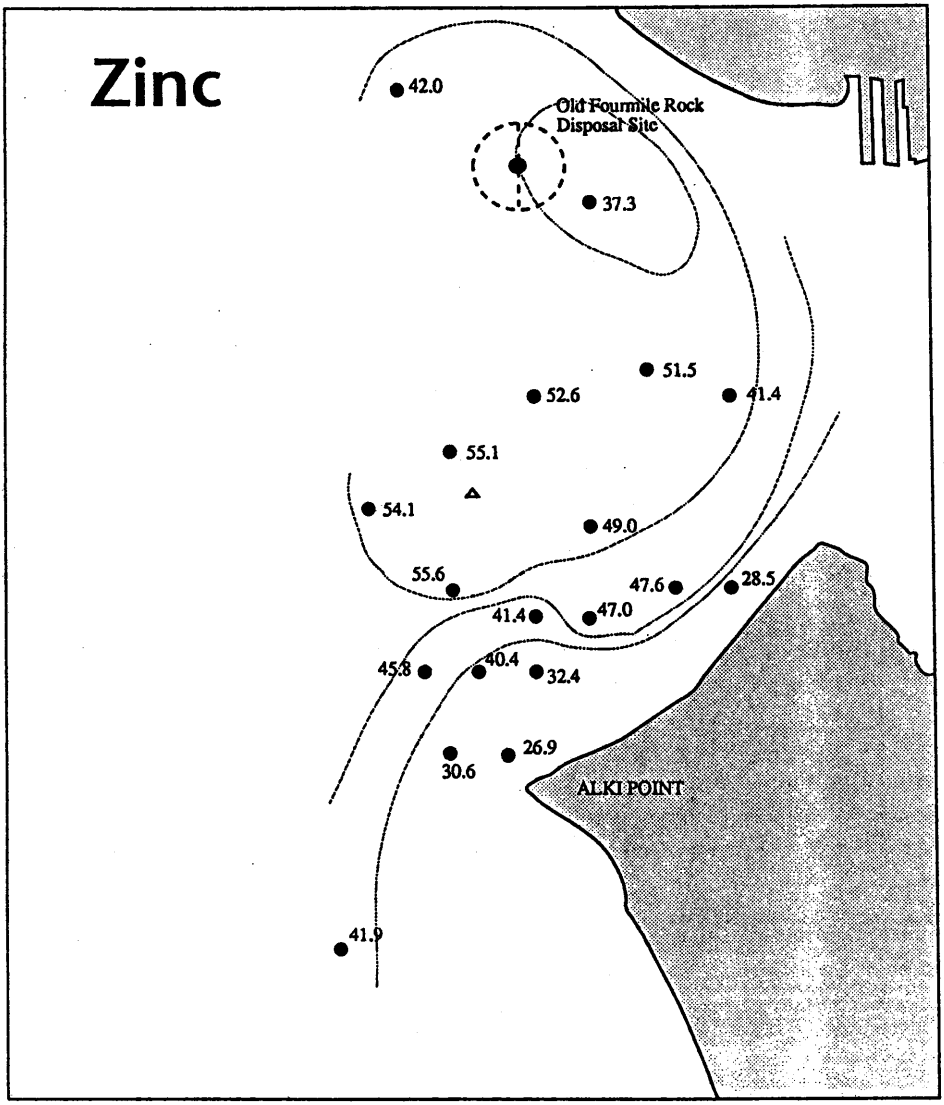

Figure 4.
ZINC MEAN CONCENTRATIONS (PARTS PER MILLION) BY STATION.

discharging to this area. It was not the purpose of our Renton outfall sediment monitoring program to analyze the effect of phasing out of the Fourmile Dredge Disposal site on the sediments around the Renton outfall. However, the data leave an impression which is hard to overlook and beyond the likelihood of random chance, that the major influence on these sediments has been the diminishing activities associated with the Fourmile Rock Dredge Disposal Site.

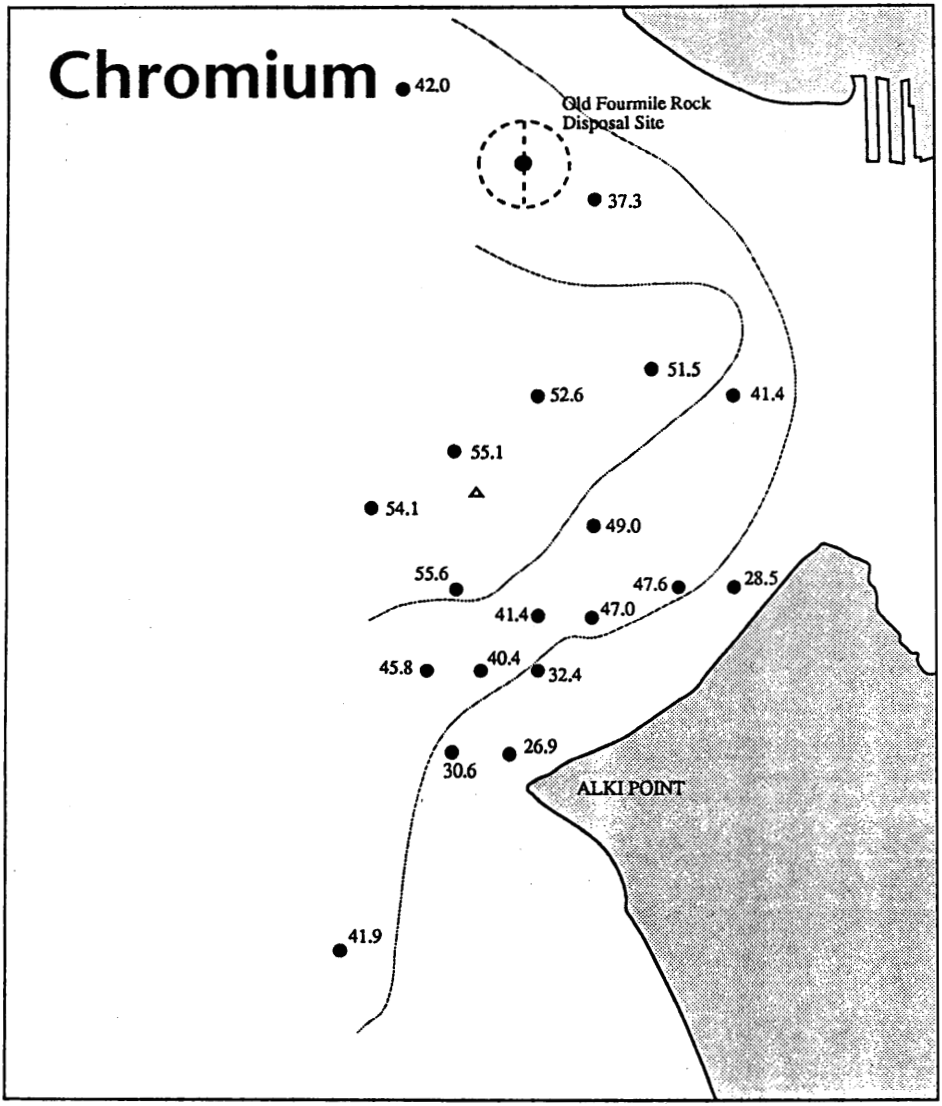

Figure 5.
CHROMIUM MEAN CONCENTRATIONS (PARTS PER MILLION) BY STATION.

The levels of *Clostridium perfringens* have increased at nearly all of the deep water sediments stations in outer Elliott Bay since the Renton outfall began discharging. Much higher values and wider confidence intervals in 1989 and possibly in 1988 data may reflect the susceptibility of this test parameter to variations in laboratory procedures.

PUGET SOUND

RESEARCH '91

WETLANDS AS HABITAT

Session Chair:

Thomas F. Mumford,
Washington Department of Natural Resources,
Division of Aquatic Lands

INTRODUCTION

Thomas F. Mumford[1]

I have some comments having to do primarily with semantics. The first is that the title of this session is "Wetlands as Habitat." As one of the people who works with me has pointed out, it really should be "Wetlands as Natural Communities," because a wetland is a habitat, and habitat implies function. It implies animals, it implies one particular kind of function being performed. So, when you think about wetlands, don't think about them just as habitats, but also as a variety of natural communities.

Secondly, for many years I considered myself a marine biologist. Then suddenly the Puget Sound Water Quality Authority came on the scene, the U.S. Fish & Wildlife Service defined wetlands to include the intertidal and the shallow subtidal, and we find ourselves as today with a mixture of what I call "real " wetland biologists—those who have been wetland biologists for many years—and "johnny-come-lately" wetland biologists (such as myself) that are more marine- or estuarine-oriented and who for many years probably didn't really consider themselves to be wetland biologists.

The important things to keep in mind when you are talking about the marine and estuarine wetlands, as opposed to upland wetlands, are that, first, these wetlands are actually one, continuous wetland. They do not consist of a wetland here, a wetland there, interspersed between the uplands. Secondly, these wetlands are really "edges," and, as in all ecological systems, edges are where the action is. There is a great deal of activity in them. And finally, they are very fragile.

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HISTORICAL CHANGES IN THE DISTRIBUTION OF TIDAL MARSHES, EELGRASS MEADOWS AND KELP FORESTS IN PUGET SOUND

Ronald M. Thom[1] *and LoAnn Hallum*[2]

INTRODUCTION

The amount of coastal wetlands in the United States has decreased dramatically over the past 70-100 years (Tiner, 1984). Puget Sound has lost substantial amounts of estuarine wetlands, and intertidal wetlands near urban centers have suffered the greatest changes (Bortelson et al., 1980). Canning and Stevens (1989) estimated that 58 ha (144 acres) of estuarine wetlands are being lost in Washington State annually.

To date, studies of the changes in estuarine wetlands of Puget Sound have focused on emergent marshes and tidal freshwater swamps (Bortelson et al., 1980; Boule' et al., 1983; Hutchinson, 1988). Vegetated habitats that are widespread and important to Puget Sound food webs also include macroalgal beds, eelgrass meadows and kelp forests. Loss of eelgrass and kelp due to man's activities has probably occurred, yet it is not known if these habitats have suffered declines similar to tidal marshes. Our purpose here is to summarize the present knowledge on the spatial extent of the wetland and nearshore plant assemblages in Puget Sound and contrast this with historical distributions. This paper is a summary of a larger report (Thom and Hallum, 1990) on this topic which was funded by the Office of Puget Sound of the Environmental Protection Agency (EPA).

STUDY REGIONS AND HABITATS

The study area was divided into five oceanographically defined regions (Fig. 1). We defined estuarine wetland and nearshore habitats as tidally influenced shallow water areas containing macrophytic vegetation. These habitats generally include tidal swamps and marshes, seaweed beds (not addressed by us), eelgrass meadows (dominated by *Zostera marina* and *Zostera japonica*) and kelp forests (dominated by *Nereocystis luetkeana*).

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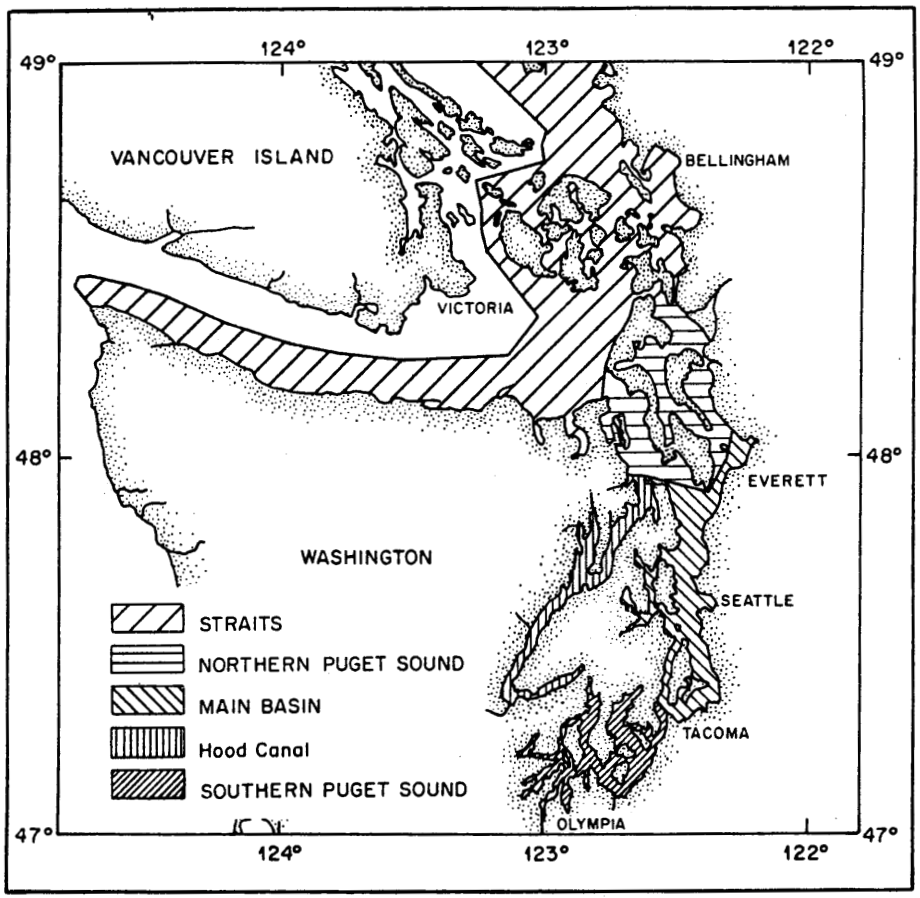

Figure 1.
PUGET SOUND AND REGIONS USED IN THE STUDY.

METHODS AND MATERIALS

Comprehensive Mapping Information

We relied on information contained in published and unpublished reports, papers, field notes, aerial photographs and anecdotal observations to compile the historical records (Thom and Hallum, 1990). Two comprehensive habitat mapping efforts have been done in Puget Sound that provide an indication of the present-day extent of nearshore habitats. First, the Coastal Zone Atlas (CZA; Albright et al., 1980) consists of folio sized maps of nearshore habitats in Puget Sound which were based on aerial photographs and ground truthing. The second mapping effort was conducted by the U.S. Fish and Wildlife

Service (U.S.F.W.S.; 1987), and consists of a series of maps at a scale of 1:12,000 referred to as the National Wetland Inventory (NWI) maps. Also of importance are the vertical color aerial photographs (scale = 1:6,000) of much of the shoreline of Puget Sound produced by the EPA (Duggan, 1982), and the 1988 habitat mapping effort by the EPA and the Washington Department of Natural Resources (WDNR; Mumford et al., 1990). The latter work covers 66% of the shoreline, and was conducted to develop the methodology for monitoring nearshore habitats through time.

Tidal Marshes and Swamps

Changes in the extent of tidal marshes and swamps have been well documented. We relied on the information in Bortelson et al. (1980), Boule' et al. (1983) and Hutchinson (1988) for summaries of changes in these habitats. These studies focus on changes in 11 major deltas in Puget Sound. Of historical note is the publication by Nesbit (1885), which summarizes the extent of tidal marshes and swamps as of approximately 1883 in the Puget Sound region. Owing to their importance to waterfowl, the Skagit and Stillaguamish River deltas have been the subject of study for over 40 years by wildlife biologists. The area of marsh in these two deltas was intensively mapped in 1947 (Jeffrey, 1947) and again in 1974 (Brewer, 1980). We compared the data from these latter efforts with changes estimated from navigation maps for the same regions (i.e, Bortelson et al., 1980).

Eelgrass Meadows

Very little historical information is available for eelgrass. "Grass" was indicated on 19th century hydrographic charts from Bellingham Bay (1855), Padilla Bay (1887) and Snohomish River delta (1886). Based upon the time of year (summer) and high density of depth observations, we assumed that the distribution of stands of eelgrass in significant quantities was generally well represented on these maps. Hence, we calculated areas of historical eelgrass coverage for these sites and compared these data with present-day distributions based upon aerial photographs and other information. Padilla Bay, in particular, has been mapped recently by Webber et al. (1987) and Douglas Bulthuis (Washington State Department of Ecology, unpublished maps).

Additional recent comprehensive information on eelgrass distributions is available in the field notes of Ronald Phillips (unpublished data) made during visits to 107 sites in Puget Sound during 1962-3. Phillips generally made qualitative notes on the density and condition of eelgrass as well as other plant and animal species at the sites. The Washington State Department of Fisheries (WDF) has extensive data on the location of eelgrass gathered during its surveys for herring spawn. Daniel Pentilla of WDF provided detailed information on all of the locations where eelgrass was noted during the period of 1975 to the present. We were able to verify the eelgrass distributions depicted

on the CZA maps by examining the original mylar overlays used to develop the maps (provided by W. Nelson, WDF). In some cases (e.g., Padilla Bay), large areas of eelgrass indicated on the mylar sheets were not transferred to the final maps. We quantified the amount of eelgrass for surveys by WDF and for the CZA by measuring the linear distance of shoreline (i.e., the length of the meadow patch) occupied by eelgrass for each region.

Kelp Forests

Kelp, because it is used as a navigation aid, and because of its commercial importance as a source of potash, had an extensive amount of historical information. Hydrographic charts as old as 1841 indicated the location of kelp. However, the most comprehensive and complete survey is that of Rigg (1915) in which the location of all major forests in the state were drawn on 9 maps at a scale of 1:100,000. Kelp forests were similarly mapped during the surveys for the CZA in 1977. We obtained from Richard Albright (EPA) the original copies of the navigation charts which were used in the field to mark the location of kelp forests. Although method differed between the studies (i.e., Rigg used a boat, Albright used an airplane), both observations are comprehensive for Puget Sound. We quantified the amount of kelp for each survey by measuring the linear distance of shoreline occupied by kelp patches.

Introduced Species

Among several species introduced in this century to Puget Sound, three are either beginning to outcompete native species or are threatening to colonize formerly unvegetated areas. Cordgrass (*Spartina* spp.) was transplanted for duck habitat and to stabilize dikes, and was probably inadvertently introduced with the import of eastern oysters. A map of the present known distribution of *Spartina* was provided by Thomas Mumford (WDNR). Japanese eelgrass (*Z. japonica*) was introduced through importation of oyster seed from Japan. This annual species now occupies extensive areas in Padilla Bay and other embayments in Northern Puget Sound. The brown seaweed *Sargassum muticum* was introduced to British Columbia and Washington through the importation of oyster seed. Although there is little information on its present distribution, unpublished data collected since 1979 at Alki beach in Seattle was used here to illustrate the effect of this invasive species on native kelp.

RESULTS

Tidal Marshes and Swamps

On the basis of surveys by Nesbit (1885), tidal marshes and swamps covered a total of 26,792 ha in 7 of the 9 counties bordering Puget Sound in the 1880s. About 405 ha had been diked by the time of Nesbit's survey. The original

Skagit-Stillaguamish tidelands covered approximately 520 km² (200 mi²) within 20 km of the present shoreline. Swinomish tide marsh, now behind dikes, was 14.5 km (9 mi) long, connecting Skagit delta with Padilla Bay. Overall, tidal marshes greatly exceeded tidal flats in area in Puget Sound in the 1880s. Nesbit estimated that the freshwater marshes of the Puget Sound area were 3-4 times as great in area as compared with the tide marshes.

There has been a 47% decline in the area covered by tidal marshes and swamps in Puget Sound (Table 1). However, the data summarized in Table 1 do not consider the original (ca., 1880) extent of marshes in the Skagit-Stillaguamish system as documented by Nesbit (1885). Hence, the actual decline over the past 100 years is probably much greater than 47%. Changes in marsh areas in the Skagit and Stillaguamish deltas based on the analyses of Bortelson et al. (1980) and Brewer (1980) are shown in Figure 2. The data of Brewer indicate that the marsh area is increasing in both deltas, whereas expansion of the marsh is indicated for the Stillaguamish only, based on Bortelson et al. This latter comparison suggests that caution must be used when viewing any analysis of changes in habitat distributions.

Table 1.
COMPARISON OF HISTORICAL AND PRESENT DAY SUBAERIAL AND INTERTIDAL WETLAND AREAS IN MAJOR DELTAS IN PUGET SOUND. *Data summarized from Bortelson et al., (1980) and Hutchinson (1988). Definitions of wetland types are according to Bortelson et al. The subaerial values are for 11 major deltas. The intertidal wetland values include only 8 of 11 deltas. Historical records for the Samish, Stillaguamish and Skagit deltas were not available.*

	Area (km²)		Change	
Wetland Type	*Historical*	*Present*	*Area (km²)*	*Percent*
Subaerial	94.1	39.4	-54.7	-58.1
Intertidal	67.9	46.7	-21.2	-31.2
TOTAL	162.0	86.1	-75.9	-46.9

Eelgrass Meadows

On the basis of information provided by WDF, eelgrass meadows have been observed on 393 km of coastline in the study area (Table 2). However, approximately 36% of the shoreline has not been surveyed by WDF, and observations by Phillips in 1962-3 indicate that much of this unsurveyed shoreline contained eelgrass. CZA surveys showed that approximately 659 km of shoreline (25% of the total shoreline length) contained eelgrass. Because eelgrass is known to exist only in the subtidal zone in many areas, the surveys for CZA probably underestimate the total distribution of eelgrass (R. Albright, per. comm.).

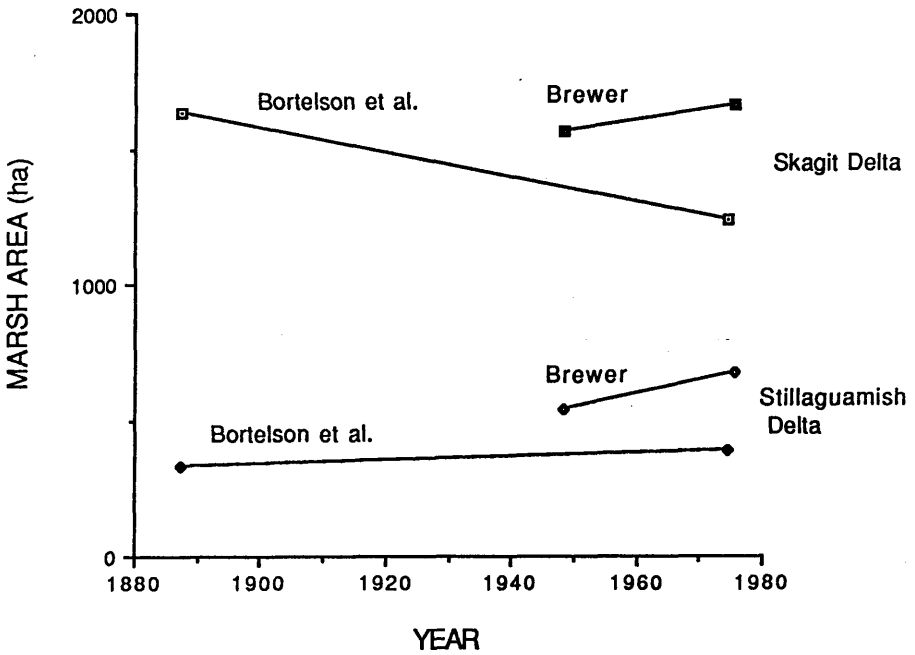

Figure 2.
***CHANGES IN MARSH AREA IN SKAGIT BAY AND THE STILLAGUAMISH RIVER DELTA** based on Bortelson et al. (1980) and Brewer (1980).*

Historical and recent data on eelgrass in three bays indicate it has declined somewhat in Bellingham Bay (-30%) and Snohomish River delta (-12%) (Table 3). In contrast, eelgrass has increased substantially in area in Padilla Bay. Examination of old and recent hydrographic charts for the Bay indicate that extensive diking has resulted in the diversion of the main flow of the Skagit River from Padilla Bay to Skagit Bay. This diversion could have resulted in increased salinities and decreased sedimentation, two factors that would enhance the habitat for eelgrass. In addition, the invading species of eelgrass, *Z. japonica*, now occupies about one third of the total eelgrass area in the Bay (Webber et al., 1987). Much of this latter area was probably unvegetated mud prior to the invasion.

Kelp Forests

The shoreline lengths occupied by kelp differed between the surveys of Rigg in 1911-12 and those of WDW in 1977 (Table 4). Overall, there was 53% more shoreline with kelp in 1977 as compared to 1911-12. In 1911- 12, 7.8% of the shoreline in the study area was bordered by kelp. Kelp occupied 12.0% of shoreline in 1977. The Straits contained the largest amount of kelp during

Table 2.
***LENGTH OF SHORELINE OCCUPIED BY EELGRASS** based on surveys by Washington Department of Fisheries (D. Pentilla, WDF, pers. comm.) and by the Washington Department of Wildlife for the Coastal Zone Atlas (CZA). The total coastline lengths for each region are given in parentheses. The percent of coastline surveyed by WDF is shown in parentheses under the eelgrass distribution.*

	WDF (1975-1989)		CZA (1977)	
Region	Eelgrass distribution (km)	Coastline with eelgrass (%)	Eelgrass distribution (km)	Coastline with eelgrass (%)
Straits (1044 km)	206 (80%)	19.8	243	23.3
N. Sound (331 km)	38 (55%)	11.6	141	42.2
Hood Canal (295 km)	96 (~100%)	32.5	104	35.2
Main Basin (455 km)	53 (78%)	11.7	146	32.1
S. Sound (497 km)	~0 (~0%)	~0	25	5.1
TOTAL (2,622 km)	393 (64%)	15.0	659	25.1

Table 3.
***HISTORICAL AND PRESENT-DAY DISTRIBUTION OF EELGRASS IN THREE PUGET SOUND BAYS.** See text for data sources.*

Bay	Year	Eelgrass Area (ha)
Bellingham	1855	48.3
	1964	34.0
Padilla	1887	598
	1986	2854
	1989	2300
Snohomish	1886	527
	1978	465

both surveys, and Hood Canal contained the least. The largest increases in kelp occurred in the Main Basin and south Puget Sound.

Rigg studied the kelp forest located on the south side of Point Williams in Fauntleroy Cove near West Seattle during 1914-1917. He noted that, at maximum development, the forest was approximately 213m. Studies of this same forest during 1974-1976 (Thom, 1978), 1985 (Thom and Hampel, 1985) and 1989 (Thom, unpublished data) indicate that the forest was at least 640 m long.

Table 4.
***LENGTH OF SHORELINE OCCUPIED BY KELP** based on surveys by Rigg in 1911-12 and Washington Department of Wildlife (WDW) in 1977. Total coastline length for each region is given in parentheses.*

Region	Shoreline with Kelp (km) Rigg 1911-12	WDW 1977	Difference (%)	Percent of Total with Kelp Rigg 1911-12	WDW 1978
Straits (1044 km)	169.8	180.6	+6.4	16.3	17.3
N. Sound (331 km)	15.9	36.3	+128.3	4.8	11.0
Hood Canal (295 km)	1.4	0.8	-42.9	0.5	0.3
Main Basin (455 km)	11.0	64.1	+482.7	2.4	14.1
S. Sound (497 km)	7.4	32.0	+332.4	1.5	6.4
TOTAL (2622 km)	205.5	313.8	+52.7	7.8	12.0

The increase may have partially been due to reduction in sedimentation at the beach by the construction of a seawall in the mid-1930s. Decreased sedimentation, coupled with natural shoreline erosion, would have uncovered more stable rock substrata to which kelp attaches (Thom and Hampel, 1985).

Introduced Species

Spartina is presently known from southern Padilla Bay, Port Susan and the Duckabush River delta (Hood Canal). The aerial extent is not documented. However, it appears that the *Spartina* in Padilla Bay has generally remained in the area where it was originally planted.

As stated above, *Z. japonica* now occupies a major portion of Padilla Bay, and is known from Drayton Harbor, Lummi Bay, and the Snohomish River delta. Phillips did not note this species during his surveys in 1962-3.

Sargassum muticum was present throughout the study area in the early 1960s as indicated in the field notes of Phillips. Quantitative data on the algal taxa in the lower intertidal zone indicate substantial changes in percentage cover of *Sargassum* and *Nereocystis* since 1979 (Fig. 3). Of note is that in 1985 harvesting of kelp became evident at this site. Harvesting involved removing the blades of kelp plants at the level of the float, effectively removing the reproductive portion of the plant.

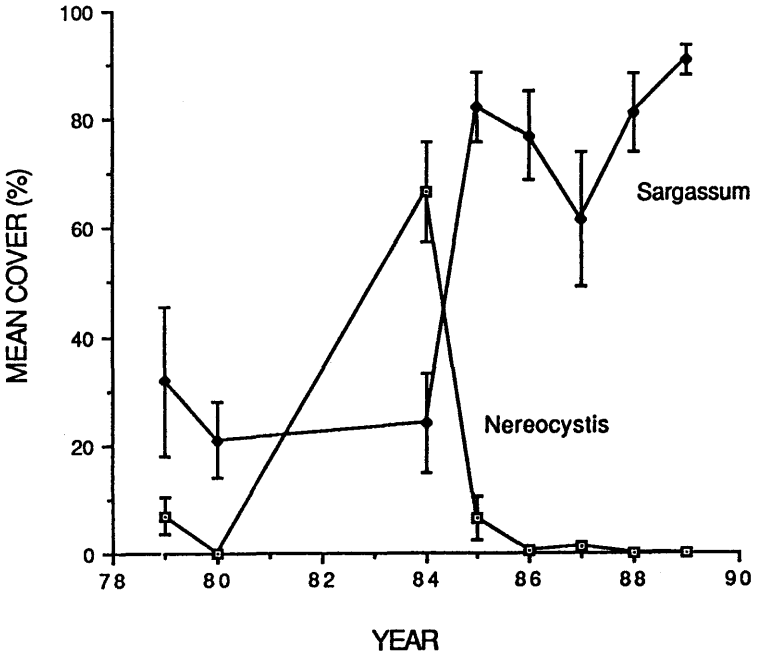

Figure 3.
CHANGES IN THE MEAN PERCENTAGE COVER (+/-SE) OF SARGASSUM MUTICUM AND NEREOCYSTIS LUETKEANA IN THE LOW INTERTIDAL ZONE (-1FT MLLW) AT ALKI BEACH.

DISCUSSION

Changes in the area covered by tidal marshes, eelgrass meadows, and kelp forests have taken place since the mid-1800s in Puget Sound. The decline in tidal marshes are the most well documented. A loss of 47% of marshes, however, probably underestimates the total decline due to the fact that changes in very large systems (e.g., the Skagit River delta) are poorly known. Eelgrass meadow changes are poorly known. It appears that some areas have seen decreases in eelgrass and some areas (Padilla Bay) have had a substantial increase in eelgrass. On the basis of two Sound-wide data sets taken 66 years apart, kelp forests may have increased their distribution this century. The greatest changes have occurred in the most urbanized regions of Puget Sound. Reasons for this increase are unclear and need study. Several introduced plant species may have affected, and probably will continue to affect, the distribution of native salt marshes, eelgrass meadows and kelp forests.

Physical disturbances (e.g, dredging, filling, diking) probably account for much of the changes in the habitat distributions. The effects of reductions in water quality, invasion by non-native macrophytes, and long-term oceanographic cycles (Ebbesmeyer et al., 1988) on nearshore macrophytes are more difficult to assess. Widespread decline in submerged aquatic vegetation in Chesapeake Bay (Orth and Moore, 1984) is attributed to eutrophication due to increased anthropogenic introductions of nutrients. Although eutrophication may not be a general concern in Puget Sound, nearshore bays and river deltas, where eelgrass and other macrophyte assemblages predominate, may be more vulnerable (Thom et al., 1988, Thom and Albright, 1990, Rensel et al., 1990). The general lack of comprehensive, quantitative data on historical distributions hinders the analysis of changes. The monitoring program presently under development by WDNR, along with other measurements proposed for the comprehensive Puget Sound Ambient Monitoring Program, are critical in documenting accurately the spatial and temporal patterns and causal factors of changes in nearshore habitats of Puget Sound.

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HOW MUCH WETLAND MITIGATION ARE WE REQUIRING? OR, IS NO NET LOSS A REALITY?

Michael Rylko and Linda Storm [1]

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) Estuary and Wetlands Programs support the national goal of no net loss of wetland acreage and function. A national goal of no overall net loss has been espoused in both the National Wetland Policy Forum Recommendations (1989) and the recent Memorandum of Agreement (MOA) signed by EPA and the U.S. Army Corps of Engineers (U.S. Army Corps/EPA, 1990). Though the MOA's goal focusses on those vegetated wetland areas which meet the criteria of the Federal Methodology for Determining Jurisdictional Wetlands (1989), this paper addresses the Puget Sound Water Quality Authority's (PSWQA) goal of no net loss of wetland acreage and function as defined by the U.S. Fish and Wildlife Service (Cowardin et al., 1979). The Cowardin system classifies all aquatic sites, except for deepwater habitats, as wetlands regardless of whether they are vegetated.

Mitigation is a tool that, in concept, has broad support from the development, environmental and regulatory communities. This support stems from the belief that mitigation can allow both private and public development to occur while still maintaining public trust interests associated with protection of aquatic resources. Sequencing procedures to avoid, minimize, and compensate wetland and other aquatic resource losses have been established to mitigate impacts to these waters of the U.S. under Section 404 of the Clean Water Act (U.S. Army Corps/EPA, 1990). For this discussion, the terms "compensatory mitigation" and "mitigation" refer to creation or restoration of wetlands as defined by Cowardin et al. (1979).

Based on a number of planning documents, policy discussions, and interagency correspondence (U.S. EPA, 1989; U.S. Army Corps/EPA, 1990; PSWQA, 1991; Conservation Foundation, 1988), it can be broadly inferred that compensatory mitigation is one of the key mechanisms for achieving no net loss of wetlands and wetland function. However, a number of other studies have demonstrated that, at least up until mid-1986, inadequate wetland mitigation planning, follow-up, documentation, monitoring, and enforcement were all contributing to the ineffectiveness of mitigation within the section 404 permitting process (Kunz et al., 1988; Cooper, 1986; Eliot, 1985).

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This study has two objectives. The first is to evaluate the effectiveness of the federal 404 program with respect to compensatory mitigation during the period 1987-1990. The second is to evaluate the contribution of the 404 program to the overall goal of offsetting the loss of wetland acreage and function. Through this and other types of critical analyses we should be able to better judge the ability of existing management and regulatory programs to attain the commonly cited goal of no net loss of wetland acreage and function.

METHODS

All projects in Washington State that received a federal 404 permit requiring compensatory mitigation were evaluated. Evaluation included: analyzing mitigation requirements, acreage ratios, net changes in habitat type and diversity, and conducting a qualitative assessment of wetland functions impacted and proposed for replacement. In addition, the frequency of specific mitigation plan elements contained within the permit file were recorded. Habitat types were defined according to the USFWS classification system (Cowardin et al., 1979). We compared the type and number of functions associated with the impacted wetlands to the type and number of functions intended by the mitigation projects. The functions lost were assessed using a qualitative method compiled by Kunz et al., (1988). The method used information in the permit file, State Environmental Policy Act (SEPA) checklists, and baseline studies. Only functions rated as having a high probability of occurrence with respect to the original wetlands were included in this comparison. Similarly, only those proposed functions of the mitigation projects that were discussed somewhere within the project files were included. This comparison was helpful in identifying classes of functions that were underrepresented in compensatory mitigation wetland design. All data reflect permit file information only. There was no field evaluation component to this study.

All data on compensatory mitigation reflect only that which was included in the Seattle District U.S. Army Corps of Engineers (Corps) and Region 10 U.S. Environmental Protection Agency (EPA) project files. Data from permits issued between 1980 and 1986 were also included in the overall analysis to provide context in which to assess recent data.

RESULTS AND DISCUSSION

Frequency of Mitigation Under Section 404

Between 1980 and 1986, 41 projects requiring compensatory mitigation were identified in Washington State, most of which were included in an earlier analysis (Kunz et al., 1988). Since 1987, approximately 32 of the 398 individual

permits (or about 8%) issued for filling waters of the U.S. under Section 404 of the CWA were found to contain requirements for wetland compensation (Table 1). This data is believed to represent almost all issued 404 permits containing compensatory mitigation within Washington state. It is possible that some projects containing compensation were not identified during the file review. This would be most likely for the year 1990. Comparative data for the wetland impacts and planned compensatory mitigations for these 73 projects is presented. Table 1 illustrates the temporal distribution of these projects over the eleven year period.

Clustering individual permits and mitigations into three size categories helps explain the apparently low number of mitigation projects relative to the number of individual permits issued (Table 2). The following discussion is based on the results listed in Table 2.

In 1987, of 116 Section 404 permits issued to fill waters of the U.S., only 16 were larger than 1 acre. Of these, 6 contained mitigation requirements. In this same year, there were also 16 permits issued for fills smaller than 1 acre but larger than 0.5 acre. Of these, 3 contained requirements for mitigation. Of the 84 permits issued in 1987 for fills smaller than 0.5 acre, 4 contained mitigation requirements. In 1988, of the 129 individual permits to fill waters of the U.S., 9 were larger than 1 acre, and of these 5 contained mitigation requirements. In 1988 none of the 40 permits for fills between 0.5 and 1.0 acres had compensatory mitigation, whereas there were requirements for mitigation in 7 out of the 80 projects that had impacts on less than 0.5 acres. The few compensatory mitigation projects identified in 1989 and 1990 may be due to delayed data entry, or possibly to a reduction in the number of projects having large impacts to wetlands and other special aquatic sites as defined in the Clean Water Act. However, the relative proportion of mitigation projects to individual permits is low.

There are several explanations for the relatively low number of mitigation projects. First, the relatively large number of permits smaller than .5 acre (many of which are closer to .1 acre) make it very difficult to even attempt to require compensatory mitigation in every permit. Second, projects which are water dependent and whose impact has been minimized to the maximum extent practicable may not have impacts considered to be significant enough to require compensatory mitigation. This determination would usually be made on balance between a project's cumulative impact and the reasonableness of mitigation requirements. Since information on cumulative impacts is usually limited, and since the relative cost of mitigation for small projects is high, often no compensatory mitigation is required. Third, compensatory mitigation to offset losses of waters of the U.S. that are not wetlands or other special aquatic sites as defined at 230.3(q-1) may not be considered as often for mitigation. Fourth, it may not be technically feasible to mitigate all permit fills (e.g., for bogs, forested wetlands, and certain subtidal fills).

Table 1.
TEMPORAL DISTRIBUTION OF REQUIRED MITIGATION PROJECTS.

Year	Number of Mitigations	Total Number Individual 404 Permits*	Total Number CWA 404 Nationwide Permits*	Number 404 CWA Applications*
1980	1			
1981	1			
1982	3			
1983	5			
1984	10			
1985	9			
1986	12			
1987	12	116	20	228
1988	13	129	81	278
1989	4	88	155	348
1990	3	65	170	433
Total 1987-1990	32	398	426	1287
Grand Total	73			

** Seattle District COE Permit Application Status System Database printout 12/05/90*

Table 2.
NUMBER OF INDIVIDUAL 404 PERMITS ISSUED FOR FILLING WATERS OF THE U.S. (I) AND COMPENSATORY MITIGATIONS (C) BY SIZE GROUPING.

	Number > 1 Acre		Number < 1 Acre > .5 Acre		Number < .5 Acre		Total	
	(I)*	(C)	(I)*	(C)	(I)*	(C)	(I)	(C)
1987	16	6	16	3	84	4	116	13
1988	9	5	40	–	80	7	129	12
1989	8	1	38	1	42	2	88	4
1990	10	2	12	1	43	–	65	3
Totals	43	14	106	5	249	13	398	32

** Approximate number estimated from Impacts and Permit Application Status System Database printout 12/05/90.*

Within this same period, 426 Nationwide permit authorizations involving fill were recorded (U.S. Army Corps of Engineers permit application status system 1990; Table 1). This number represents the minimum number of potential impacts covered by nationwide permits, since many fills may occur which do not require reporting to the Corps. Authorization under nationwide permits is not usually subject to individual agency review and therefore no mitigation is required (33 CFR 330.5).

It is important to note that while the number of individual permits has steadily decreased since 1987, the number of nationwide permit authorizations has increased quite sharply (Table 1). There are two possible explanations for this. First, the change could be attributed to improved effectiveness in reporting and recording nationwide authorizations (pers. comm., Seattle District Corps staff). Second, the efforts to minimize wetland impacts have been successful at reducing the size of many projects. This could explain the apparent shift (Table 1) from individual permit coverage to nationwide permit authorization for particular types of fills or projects. (Note: nationwide permits cannot be authorized for all project types or fills.)

Net Loss of Wetland Acreage

Based on Seattle District Corps Impact Assessment and Permit Application Status System (PASS) database printouts for 1987 through 1990, we conservatively estimate that the gross annual loss of wetlands under the Section 404 permitting program, including individual and nationwide permit authorizations, is probably close to 200 acres per year. Of this, approximately 60% could be attributed to individual permits. This is consistent with estimates by Canning and Stevens (1989) of 185 acres per year, which did not include nationwide permit authorizations and were considered "extremely conservative". Using these estimates and comparing them to the annual compensatory mitigation acreage provided (Figure 1), it appears that only 10% of the total acreage of aquatic resources impacted through the 404 program required compensatory mitigation.

Kunz et al. (1988) cite a planned acreage replacement ratio of only 67% for 35 compensatory mitigations between 1980 and 1986. In the current study, 6 additional mitigations were identified from this earlier period. The revised replacement ratio with respect to area for all 41 projects from the period 1980-1986 was 75%. Between 1987 and 1990 this ratio increased somewhat to 85%. From 1987 to 1990, plans amounting to 73 acres were used to offset the filling of 86 acres of wetlands. Only in the years 1986, 1987, and 1989 was the annual planned compensation acreage greater than the corresponding acreage lost (Figure 1). Combining the 26 projects containing mitigation from these three years amounts to an average replacement ratio of 107%.

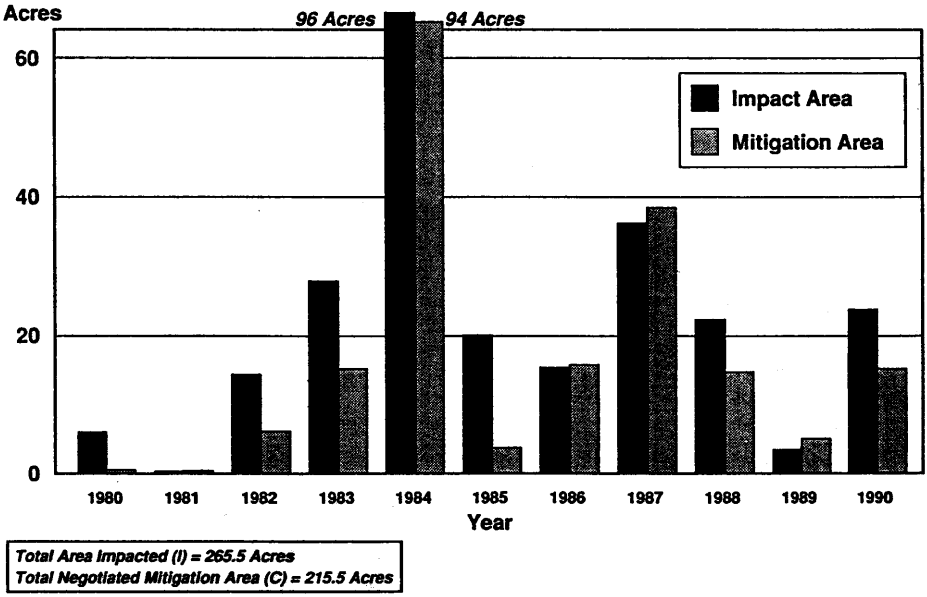

Figure 1.
REQUIRED MITIGATION AREA VS. AREA IMPACTED.

Gwin and Kentula (1990) conducted field studies to evaluate wetlands created for compensatory mitigation under Section 404 in Oregon state. They documented that "as built" projects were on average 29% smaller than site plans had depicted. One suggested reason for this discrepancy was that the upland sideslopes of created wetlands and the site access areas were included in the compensation acreage calculations. The discrepancy between what is provided on paper and what is realized in the field gives strong support for requiring compensatory mitigation at a greater than 1:1 ratio to ensure at least 1:1 replacement. Gwin and Kentula's study suggests a minimum 1.3 to 1.0 ratio to ensure minimal acreage replacement. This may not be enough when replacement of wetland habitat diversity, functions and values are also considered.

Researchers in California (Race, 1985; Eliot, 1985; Baker, 1984) have shown that compensatory wetlands rarely meet design criteria to replace habitat types and functions. This provides another justification to require greater compensatory mitigation ratios.

Net Loss of Wetland Diversity

A wetland area may contain one or more habitat types. For example, one system may contain open water, a creek bed, emergent vegetation, and a

forested area, all of which are distinct habitat types within the USFWS classification system (Cowardin et al., 1979). The relative diversity of these habitat types is an important index of wetland function. The number of habitat types can be used as an easily measured diversity index.

For those 404 permits issued between 1980 and 1986 which included compensatory mitigation, there was approximately a 27% net loss, on paper, in the number of habitat types (Figure 2). This trend continued through 1987. From 1988 to 1990, 97% of the habitats impacted were planned for replacement (Figure 2). This improvement may be attributed to the increased emphasis agencies have placed on the importance of replacing wetland functions as well as wetland acreage.

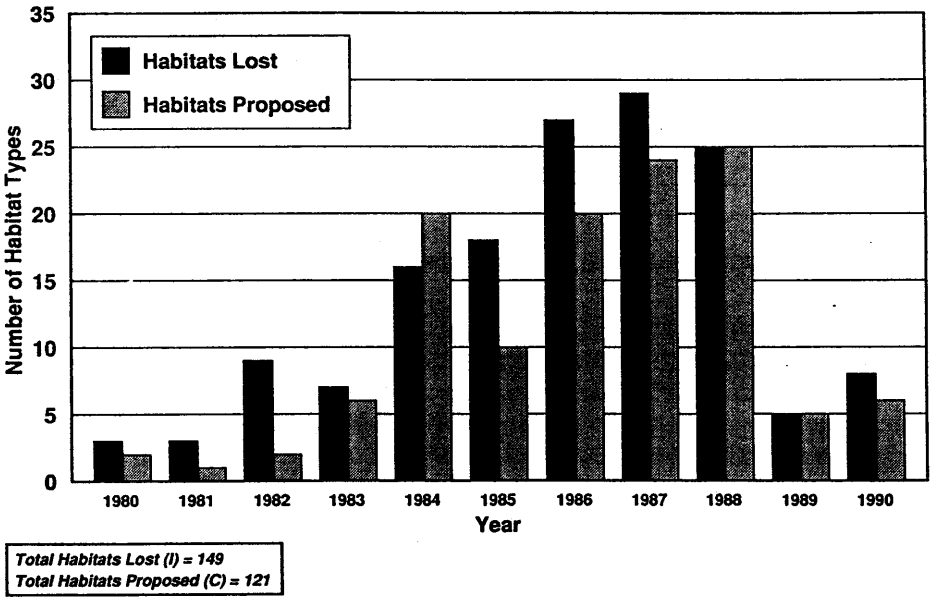

Figure 2.
NUMBER OF HABITAT TYPES LOST AND PROPOSED AS MITIGATION.

Between 1980 and 1986 estuarine systems were most often impacted and also had the highest rate of replacement. From 1987 to 1990 estuarine systems were still the most commonly impacted, with respect to those projects involving compensatory mitigation, but the estuarine systems had the lowest replacement rate during this later period (Table 3). In a number of projects, palustrine habitats were used to mitigate the loss of estuarine areas. Conversely, by comparing the data between 1980 and 1986 to that of 1987 and 1990, a substantial improvement in replacing palustrine and riverine wetland habitat types is evident (Table 3). Many of the riverine mitigations were

Table 3.
NUMBERS OF MAJOR HABITAT TYPES IMPACTED AND PROPOSED

	Lacustrine	Riverine	Palustrine	Estuarine	Total
1980-1986					
No. Impacted	9	14	25	32	80
No. Proposed	8	6	12	31	57
% Replacement	(89%)	(43%)	(48%)	(97%)	(71%)
1987-1990					
No. Impacted	6	11	24	26	67
No. Proposed	6	11	23	20	60
% Replacement	(100%)	(100%)	(96%)	(77%)	(90%)

centered around riparian plantings and enhancing shoreline areas. However, many of the riparian enhancements may not meet the Cowardin definition of a wetland.

Net Loss of Wetland Functions

All of the articulated no net loss goals include specific reference to no net loss of both function and acreage (Conservation Foundation, 1988; U.S. Army Corps/EPA, 1990; U.S.Fish & Wildlife Service, 1990; PSWQA, 1991). However, methods for assessing the functions of diverse habitat types and wetland systems have not yet been standardized. Often compensatory mitigation plans are not consistent in providing baseline data on wetlands to be impacted or adequate monitoring to demonstrate functional replacement with compensatory mitigation (Kunz et al., 1988).

Figure 3 illustrates the cumulative tradeoffs of wetland function over the last eleven years and also from 1987-1990. It is apparent that not all wetland functions are equally proposed for replacement. On a percentage basis, fish habitat, food chain support, and flood storage were most frequently targeted for replacement. While we can see substantial improvement in the last four years, wildlife habitat function still appears to be under-represented and shoreline stabilization objectives appear to outnumber actual impacts to this function by 300% (Figure 3). Both of these trends may be worth monitoring in the future.

Sediment trapping and nutrient retention were generally not considered at all (Figure 3). This may be because they are functions assumed to develop with compensatory wetland establishment. They may also be considered of lesser priority by resource agencies whose mandates emphasize protection of fish and wildlife habitat. These results are consistent with observations by Baker (1984) from studies on San Francisco Bay; rarely is the objective of mitigation plans to replace the full spectrum of wetland functions.

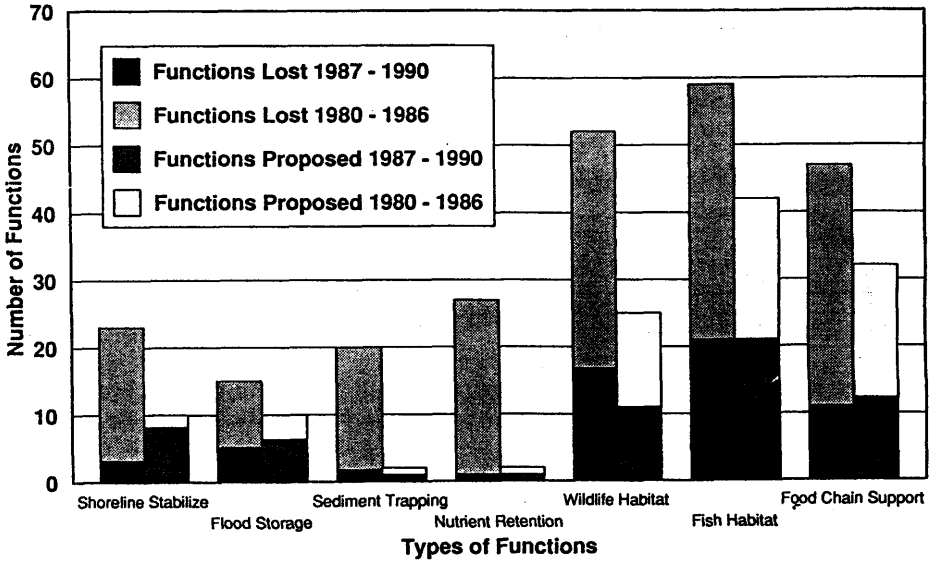

Figure 3.
TYPES AND NUMBERS OF FUNCTIONS LOST VS. FUNCTIONS PROPOSED AS MITIGATION.

Not all planned mitigation objectives are always achieved. However, it is also true that a created or restored wetland may develop functions not originally part of the planned functional replacement. Standard monitoring of mitigation projects may better characterize the actual functions of compensatory wetlands in addition to those that are specifically targeted in mitigation plans.

Wetland Losses Occur In Time As Well As In Space

Because dates of project and mitigation initiation and completion are not routinely tracked, we did not specifically evaluate time lags between wetland impact and mitigation completion from the period 1987 through 1990. Extensive time lags between project impact and mitigation initiation were cited by Kunz et al. (1988). These lags represented losses of at least 1 to 3 growing seasons (i.e., years) per project. None of the mitigation projects reviewed

between 1980 and 1986 addressed this temporal loss of resource function as a value incorporated into the mitigation. Likewise, none of the recent mitigations addressed this type of loss. Unless the mitigation is completed some time prior to the destruction of the original wetland, this functional loss of wetland will occur.

Inconsistent Incorporation of Mitigation Elements and Design Criteria

Figure 4 illustrates how frequently 404 permits, which contained compensatory mitigation, included specific reference to key elements of the required mitigation project. If any of the referenced (Figure 4) elements were incorporated in the written permit, the mitigation plan, project drawings, or drawing notes, that element was included in this tally. To illustrate program trends, the data is grouped into two time periods, 1980-1986 and 1987-1990. Significant progress can be seen across almost all elements. Two particularly important trends are shown by the increase in occurrence of general goals statements and monitoring requirements during the later period. The permits themselves now commonly reference mitigation when it is required.

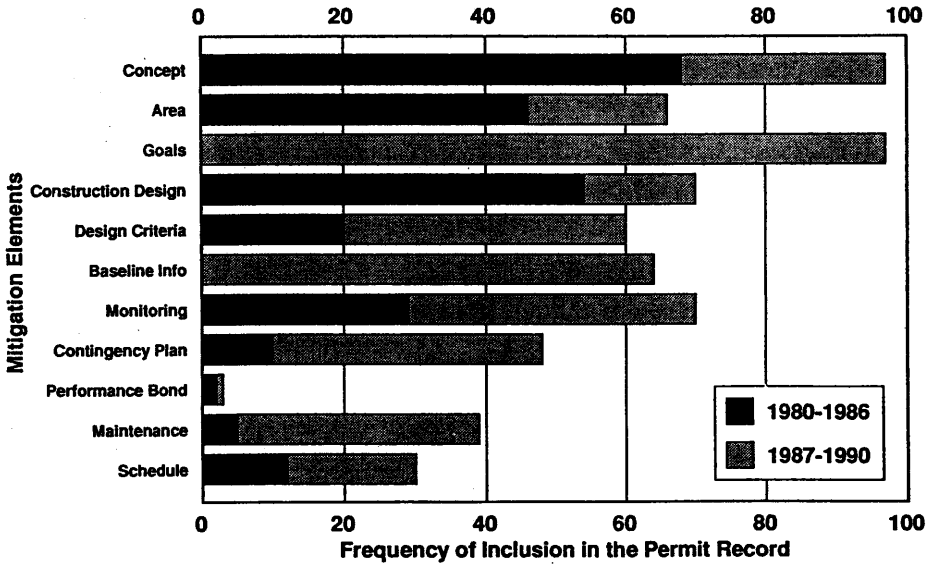

Figure 4.
FREQUENCY WITH WHICH MITIGATION ELEMENTS WERE INCLUDED IN THE 404 PERMIT RECORD.

Room for improvement lies in specifying other critical elements. Clear descriptions and detailed baseline data (acreage, functional assessment and habitat types) of areas impacted and those planned for restoration or creation are still lacking in 35% of the permit records. The same can be said for the need to better identify general construction designs (e.g., excavation to a specific slope or description of hydrological modification), specific design criteria (e.g., attaining a minimum vegetation or invertebrate density), monitoring to document attainment of design criteria, maintenance agreements, and clearly outlined construction schedules. Rarely are performance bonds required, even though USFWS designed an efficient and practical model for such contingency measures (Dorotich Marina project, COE permit 071OYB-2-10979). Use of a performance bond provides additional incentive for ensuring that mitigation is implemented, that monitoring is conducted, and that reports are submitted in accordance with permit conditions. "As built" project plans were never required but are strongly recommended by Gwin and Kentula (1990).

Since wetland restoration and creation is still an experimental science, even the best intentioned and designed projects may not always function as planned. Clearly, routine follow-up in the form of compliance tracking, project monitoring for success/failure, and contingency planning are needed. The inclusion of such elements not only provides clear accountability and enforcement mechanisms, but it also ensures that the applicant and agent thoroughly consider important design detail well in advance of construction. Mason and Slocum (1987; cited in Gwin and Kentula, 1990) concluded that when permits contained specific conditions for wetland mitigation, 86% were considered successful, whereas only 44% of projects without specific permit conditions could be considered so. They also concluded that the inclusion of specific deadlines doubled the success rate.

CONCLUSIONS

1. Since 1987 there has been substantial progress in the 404 program in developing compensatory mitigation requirements. For many project permits, the mitigation requirements were well designed, considering the constraints inherent in the regulatory process. Some other mitigation requirements and designs were poorly documented and heavily affected the apparent overall effectiveness of the 404 program.
2. As the 404 program is currently structured with respect to compensatory mitigation, it is unlikely that existing program staff could require mitigation for every individual fill permit. Also, considering opportunity cost, it is not clear if heavily increased staffing would get us measurably closer to our actual goal of no overall net loss.

3. Based on the most recent estimate of total wetland loss in Washington State (compiled by Canning and Stevens, 1989)—about 2300 acres per year—it becomes important to acknowledge that only about 10% of these wetland impacts are authorized through the federal 404 program. The implications for realizing no net loss for the state as a whole become clear; existing federal programs alone cannot be expected to maintain the resource protection goals of the state.

RECOMMENDATIONS

1. Compensation acreage ratios should be increased so that they exceed 1:1 by an adequate margin. A review of such margins has been investigated by the Department of Ecology's Wetlands section and will be included in the Puget Sound Management Plan. The federal agencies associated with 404 permit review and issuance should review and incorporate Ecology's findings into the 404 program as appropriate.
2. 'As built' drawings of mitigation projects would be of great benefit to project follow up and would provide valuable information on the effectiveness of compensation requirements. Site specific monitoring would still be necessary to evaluate the ecological success of the project. In addition, site specific monitoring and project evaluation could be given more attention.
3. All mitigation elements should be clearly described and included in every mitigation plan. The mitigation plan in turn should always be made an enforceable condition of the 404 permit.
4. Alternative mechanisms for attaining no net loss within the 404 program should be considered. For example, non-compensatory restoration efforts, initiated by and coordinated through any of the involved agencies or the private sector, could be used to offset outstanding wetland losses including those associated with nationwide authorizations.
5. Federal, state, and local government should strive to accomplish wetland conservation goals within their respective permitting programs. Local governments must begin implementing conservation strategies that are targeted at no net loss within their own jurisdiction. This is the specific intent of Wetland Program Element 4.1 of the Puget Sound Management Plan.

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AN ASSESSMENT OF WETLAND MITIGATION REQUIRED THROUGH SEPA IN WASHINGTON

Peggy Bill, Michelle Stevens, and Andy McMillan [1]

INTRODUCTION

In spite of increased efforts to protect wetlands, Washington State continues to lose between 900 and 2000 acres of wetlands per year due to draining and filling for agricultural activities and development (Canning, 1989). With increasing scarcity, the ecological value of every acre of wetland increases. In response to public concern for wetland losses, the National Wetlands Policy Forum recommended that a national wetland protection policy be adopted to achieve no net loss of the nation's remaining wetlands, including restoration and creation to increase the quality and quantity of the nation's wetlands resource base. Wetlands mitigation is commonly viewed as an important means of achieving "no net loss" of wetlands functions, values, and acreage by requiring projects to avoid or minimize impacts, or by requiring compensation for unavoidable impacts through wetland creation, restoration, preservation, and enhancement. This paper will provide an assessment of wetlands mitigation required through Washington's State Environmental Policy Act (SEPA).

Through SEPA, mitigation is defined as:

- Avoiding the impact altogether by not taking a certain action or part of an action;
- Minimizing impacts by limiting the degree of magnitude of the action and its implementation, by using appropriate technology, or by taking affirmative steps to avoid or reduce impacts;
- Rectifying the impact by repairing, rehabilitating, or restoring the affected environment;
- Reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action;
- Compensating for the impact by replacing, enhancing, or providing substitute resources or environments;
- Monitoring the impact and taking corrective measures.

It is generally accepted that these measures are considered in a descending order of preference. Wetland mitigation for individual actions may include a combination of conditions and may include wetland restoration, enhance-

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ment, creation, or preservation. Compensatory mitigation is usually required only after all attempts to avoid or minimize impacts.

The debate over the effectiveness of wetlands mitigation in meeting the objectives of no net loss is escalating. Much of the current concern is centered around the lack of technology and expertise in the field of wetland restoration and creation. Replacement of functions and values is implicit within the objectives of compensatory wetlands mitigation and requires a sophisticated level of understanding of highly complex ecosystems.

Several studies have recently documented that past compensatory mitigation attempts have most often fallen short of actual replacement, either in function, time or space. An assessment of wetland mitigation practices associated with Section 404 in Washington State by Kunz et al. (1988) documented that planned mitigation resulted in a net loss of wetland acreage and diversity. An evaluation of 35 projects which occurred between 1980 and 1986 showed a proposed replacement rate of 67% of original acreage, and 68% replacement of original habitat. No field evaluations were included with this study; thus it represents only the proposed replacement as it is presented in the mitigation plan, and does not include an assessment of as-built conditions in the field. In addition, Kunz et al. found that wetland losses occurred in time as well as function and acreage; only 6% (2) of the projects were completed prior to the elimination of the original wetland. These findings were supported in a study by Kentula et al. (in prep.) which documented a total net loss of 120 acres of wetlands for 90 permits issued in Washington and Oregon. Wetland types created were most often different from the original impacted wetland, with the greatest net loss of freshwater marshes.

Further losses of wetlands were documented in a study evaluating wetlands protection through SEPA for those areas which fall outside the jurisdiction of 404 and SMA (Hull and MacIvor, 1987). In summary, the study found that SEPA checklists do not accurately identify the presence of wetlands and potential impacts. Of the sites evaluated which did not mention wetlands on the environmental checklist, 47% were actually found to have wetlands on site. The study also documented that forested and persistent emergent wetlands of under five acres in size appear to be most at risk.

METHODOLOGY

The study was based on an evaluation of 20 mitigation sites required through SEPA in Western Washington. Originally, sites included within the study were to have been completed for at least two years. Sites were identified by contacting 15 local jurisdictions within Western Washington in which wetlands mitigation might be expected. Counties which had developed environmentally sensitive area ordinances, such as King County and Island County,

were originally not included, since it was assumed that these jurisdictions were more likely to monitor and require implementation of the wetland mitigation projects. Very few sites were identified which had been complete for at least two years. This criteria was subsequently changed to require that sites had been constructed and planted. Only 14 sites were identified which met the criteria for the study, requiring the inclusion of six sites from King County. Therefore, these sites do not reflect a random sampling of mitigation sites in Western Washington, but instead represent the majority of the initial mitigation projects in Western Washington which have been required through SEPA.

The files of each site were then reviewed to extract information concerning the required mitigation conditions. Ideally, this included: SEPA threshold determination (DNS, DS, or MDNS), information on the original site characteristics, permit conditions, site plans, mitigation goals, contingency plans, monitoring reports or requirements, and bonding requirements.

This review was followed by a field assessment of each site. The objectives of the site inspection were to determine compliance with stated mitigation conditions and to assess the viability and persistence of the wetland system with the landscape. Specific conditions which were stated within the mitigation plan were evaluated, including hydrology, construction, acreage, buffer, and vegetation. Planted vegetation as well as naturally occurring and invasive species were noted. Indication of use of the area by wildlife was also noted, as well as an assessment of site degradation or problems. Degradation was defined as impacts which do not pose an immediate threat to the wetland, but which may result in the eventual loss of certain functions or values. Hydrology was generally evaluated in terms of connectivity and in relation to any conditions presented in the site plan.

RESULTS AND DISCUSSION

Mitigation has not as yet been fully incorporated within SEPA for most jurisdictions in Western Washington. This point is emphasized by the fact that it was impossible to locate even the 20 completed sites desired for the study. Most jurisdictions stated that use of mitigation through SEPA is only recently being utilized, while a few stated that no mitigation is being required. Sixty percent (12) were permitted in 1987, with the rest fairly evenly distributed between 1984 and 1988. An analysis of type of project found that 60% (12) were required for residential developments, 35% (7) were for commercial projects, and one was mitigation required for the construction of a school. The lack of a general understanding of wetlands mitigation as well as a lack of consistent definition was also evident.

Information supplied within the files concerning mitigation requirements was most often incomplete or not specifically stated. Sixty percent (12) of the projects were missing components generally considered necessary for mitigation, including original site description, mitigation goals, planting requirements, monitoring requirements and objectives, contingency plans, and bonding requirements. Only 10% (2) of the projects adequately addressed all of the issues. This problem provides a major obstacle for anyone trying to track or enforce wetlands mitigation. Further, compliance with oftentimes elusive or unstated conditions is difficult, and at times, impossible, to determine.

There was an 84% replacement ratio for acreage in mitigation plans, representing a net loss in acreage. Only 30% (6) of the plans included information needed to determine replacement ratio (the acreage for the original wetland as well as acreage for the mitigation site), yet the replacement ranged from 10-170%. This information, when included with extensive problems of compliance in the field, suggests that this figure is a low representation of actual replacement of functioning wetland acreage.

Mitigation resulted in a net loss in some types of wetland types, and an increase in others. All of the mitigation projects evaluated involved freshwater systems. Mitigation resulted in a 64% decease in palustrine emergent wetlands, and a 325% increase in palustrine open water wetlands, mostly as small ponds created for stormwater detention or as a visual amenity for the project. There was neither a net loss or gain in palustrine scrub-shrub or forested wetlands. Forested wetlands which were present on-site were protected as part of the mitigation.

On-site mitigation was required for the majority of projects, with an equal percentage of in-kind and out-of-kind replacement. Forty-eight percent (11) were in-kind, 52% (12) were out-of-kind, while 100% involved on-site mitigation. Only two required both on- and off-site mitigation. This is significant, as it documents that in-kind replacement is most often not required, and when evaluated in relation to the change in percentage of certain wetland types, suggests that mitigation appears to be used to satisfy other needs of the developer.

Compliance problems were identified for more than 50% of the sites that were completed. Compliance problems included: 1) substitution of other plants for required species; 2) inadequate density or location of plantings; 3) inadequate construction of the required slopes, acreage, or structure; 4) insufficient hydrology; or 5) the timing of the completion of the mitigation.

Only 10% (2) sites were completed before construction and subsequent elimination of the original wetland. This concurs with the finding of Kunz et al. (1988) that wetland losses occurred in time as well as space, and emphasizes

that successful compensatory wetland mitigation requires the establishment of a functioning system prior to the elimination of the existing wetland to achieve no net loss of wetland function and value over time as well as space.

Site degradation was found in 63% (13) of the sites. Sites were identified as degraded if there were visible problems such as siltation, logging, removal of vegetation, loss of wildlife habitat due to proximity of development, problems with hydrology (including water quality or quantity), signs of pet predation, or the presence of garbage.

Only 57% (11) of the mitigation projects indicated that monitoring of the site was required after completion of the project. Of those, six required two years of monitoring, seven required three years, and one each required one year and five years. Only a few plans specified the conditions to be monitored, yet it was implied that the persistence of the planted wetland vegetation was the main criteria to be evaluated. Only one site addressed the need to monitor the hydrology of the system.

Only four plans specifically addressed the amount and purpose of required bonding, several jurisdictions indicated a general policy of requiring bonding, and one jurisdiction stated that no bonding is required. Again, successful establishment of the planted vegetation was considered to be the most important criteria, yet timing for determining establishment was not specified. Several jurisdictions noted that very few sites have actually received a final inspection. It appears that the amount required for the bond is not enough incentive to require compliance.

RECOMMENDATIONS

The results of this study indicate that mitigation continues to fail to provide an adequate means of compensating for unavoidable impact to wetlands, and highlights weak links in the process. Recommendations for dealing with these weak links include: 1) restructuring the environmental checklist of SEPA to effectively reflect the presence of wetlands; 2) providing local government staff with training, including information concerning recommended replacement ratios, restoration and creation criteria and design, sources of information, and an understanding of the complexity and long-term commitment required for successful mitigation; and 3) adoption of a uniform, structured format which clearly defines the required criteria for use in the development of mitigation plans.

Criteria which appeared to contribute to successful mitigation included: 1) clear statement of mitigation goals based on an understanding of the function, values, and acreage of the original wetland; 2) persistence in the landscape,

including hydrologic connectivity with an existing, functioning system; 3) diversity of habitat which spatially and structurally resembles a natural system, including reestablishment of a diversity of native species and the presence of dead snags and logs; 4) utilization of plants and soil from impacted wetland, supplemented as necessary with native species from nursery stock; 5) establishment of adequate buffers that will provide necessary protection; 6) establishment of a functioning system prior to or simultaneous with impact to original wetland; 7) a clear statement of monitoring objectives, including water quality, control of invasive species, and modification of the hydrology until the system is well established and functioning; and 8) development of a contingency plan which addresses the potential need and responsibility to modify the wetland construction or hydrology over time to achieve a functioning system that requires minimal maintenance.

CONCLUSIONS

On the basis of these findings, it is questionable whether current mitigation as required through SEPA is creating wetlands that can be defined as fully functioning ecosystems that will persist through time. Wetlands mitigation should not be seen as justification for the elimination of viable wetland ecosystems that provide a multiplicity of functions and values. Until the time that the technology of wetland creation and restoration has moved beyond the experimental stages, a realistic evaluation of the probabilities of success must be incorporated in mitigation policy, and increased efforts should be directed towards protection of the existing resources.

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INTEGRATING WETLAND RESOURCE CONSERVATION STRATEGIES: AN APPLICATION OF NON-COMPENSATORY RESTORATION

Curtis D. Tanner[1] *and Michael Rylko*[2]

INTRODUCTION

Our nation has progressed from an era of disdain and wanton destruction of wetlands to a period of increasing recognition of the importance of this resource. While private development is often blamed for destroying wetlands, it should also be recognized that the activities of governments at all levels share responsibility for this. Road construction, sewer and water systems, port development, and waste disposal have all contributed directly to the degradation and loss of wetlands. Although compensatory mitigation is relied upon to hold the line on wetland losses, the effectiveness in achieving this goal is debated (i.e., see Tanner, 1990, for a review of mitigation policy critiques). In Washington State, advances in mitigation requirements have improved and wetland losses have declined, but compensation continues to fail to keep up with development project losses (Rylko and Storm, this volume). Thus, the concept of restoration outside the arena of regulatory mitigation as partially a public responsibility must be investigated.

To achieve policy goals of no net loss and ultimate gains in wetland area and function (Conservation Foundation, 1988; PSWQA, 1991), significant reforms will be required, including a substantial reduction in the rate at which existing wetlands are being lost, and a substantial increase in efforts to restore wetlands. To achieve net gains and an enhancement of damaged wetland ecosystems, either mitigation projects must be required to provide benefits beyond individual project impacts, or mechanisms of non-compensatory restoration must be employed. To rely on the former would clearly raise questions of equity, if not legality. Therefore, new approaches beyond regulation and compensation must be explored. It is the intent of this paper to stimulate discussion leading to novel approaches. Using the Duwamish River estuary as a pilot study, this paper will seek to make three general points: (1) restoration of estuarine system function is an important goal from both policy and ecological perspectives; (2) available opportunities exist for such restoration in the Duwamish River estuary; and (3) a variety of public programs could be utilized to implement identified opportunities.

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MAINTAINING SYSTEM FUNCTION

Estuaries are complex and unique ecosystems that provide a variety of important functions; the role of estuaries as fish and wildlife habitat provides a useful example. Relatively high primary productivity combined with inter- (i.e. upstream) and intra-system detrital material support an essential assemblage of primary consumers. These organisms in turn are relied upon by a variety of secondary and higher level consumers (Thom, 1987), many of which have societal value. Because of the interrelatedness of different habitats within an estuary and the requirements of many animals for attributes from a variety of these habitats, preservation of estuarine system function requires an ecosystem approach. Spatial pattern has been shown to influence many processes that are ecologically important. Therefore, the effects of pattern on process (i.e. function) must be considered (Turner, 1989). To do so, it will be necessary to adopt an estuary-wide perspective that identifies all available siting opportunities, the potential benefits provided by the sites, and factors that augment or detract from important functions.

A variety of authors have described the need for policies that encompass a greater scale than the individual project. McCreary (1982) advocated using "watersheds as the unit for analysis for coping with wetland and estuarine issues". Ashe (1982) pointed to the need for an "ecosystem-oriented approach". Good (1987) called for regional restoration goals and an estuary-wide approach to mitigation planning, and Tanner (1990) has outlined the basic elements of such an approach. However, there has been little discussion regarding the strategic differences between maintaining site function and system function, and thus between site restoration and system restoration. Clearly, the two are not mutually exclusive, but they may very well be distinct objectives.

The Duwamish River estuary has suffered extensive loss of historic wetlands. Blomberg et al. (1988) estimated that "less than two percent of the former area of shallows and flats and tidal marshes remain, while tidal swamp habitat has been completely eliminated." This has likely had a significant impact on the fish and wildlife species which depend on the intertidal habitat of this system for a variety of needs. In the Duwamish River estuary considerable resources are expended by a variety of state, tribal, and private organizations on hatcheries to sustain commercial and recreational fisheries. These efforts annually provide over 7 million juvenile chinook salmon, some 1 million coho fry, as well as chum salmon and steelhead trout. While hatchery output can be increased in response to decreased returns, wild stocks are especially vulnerable to system degradation and loss of estuarine functions. Juvenile salmonid survival depends to varying degree on estuarine wetland habitats, and chinook and chum are believed to be especially estuarine dependent, utilizing marsh and flat areas for foraging and refuge (Congleton, 1978; Congleton and

Smith, 1976; Healey, 1979, 1981). In addition to salmonid dependence on this estuary, the greenbelt adjacent to the west side of the Duwamish Waterway supports a great blue heron rookery. These animals forage in intertidal portions of the Duwamish. Other waterfowl utilize remnant wetlands on Kellogg Island for nest sites (Canning et al., 1979). Thus, despite its highly urban character, extensive wetland loss, and contaminant problems, the remnant wetlands in the Duwamish River estuary continue to provide important functions. If it is desirable to restore and enhance the functions of this system, it will be necessary to identify and critically evaluate available restoration opportunities and the mechanisms for their implementation.

SPECIFIC OPPORTUNITIES FOR ENHANCEMENT

Methods and Materials

To determine the location of potential restoration sites, undeveloped shorefront parcels were established. While it is possible that buildings could be demolished and paved areas dug up for restoration activities, it is more likely that these projects will be located on parcels not burdened with these obstructions and accompanying commercial use. The study examined all shoreline areas of the Duwamish River estuary. Under common definition (Cowardin et al., 1979), this includes portions of the river downstream of the East Marginal Way bridge (river mile 18.6, the upper extent of salinity intrusion under average low flow conditions; Santos and Stoner, 1972), to portions of Elliott Bay bounded by a line from Duwamish Head to Fourmile Rock. Aerial photographs (1:12,000) of the area for 1970 and 1989 were obtained and interpreted with the aid of a 4x stereoscope. Undeveloped shorefront parcels larger than approximately 0.5 hectares were delineated and mapped. A digitizing pad was used to estimate the area and shoreline length of identified sites. Finally, qualitative information pertaining to potential benefits or detriments of individual sites remaining in 1989 was collected.

Results

Figure 1 shows the location and configuration of undeveloped parcels existing in 1970 and 1989. While some of the sites have increased in size during this period, the overall trend has been a reduction in both the number of potential restoration sites and the total available area (Figure 2). In 1970, a total of 32 potential sites where identified; in 1989 only 26 undeveloped shorefront parcels where located. During this 19 year period, the total area of these sites declined from 130 hectares to 60 hectares. Table 1 summarizes available site-specific data pertaining to restoration and habitat potential for 1989 sites.

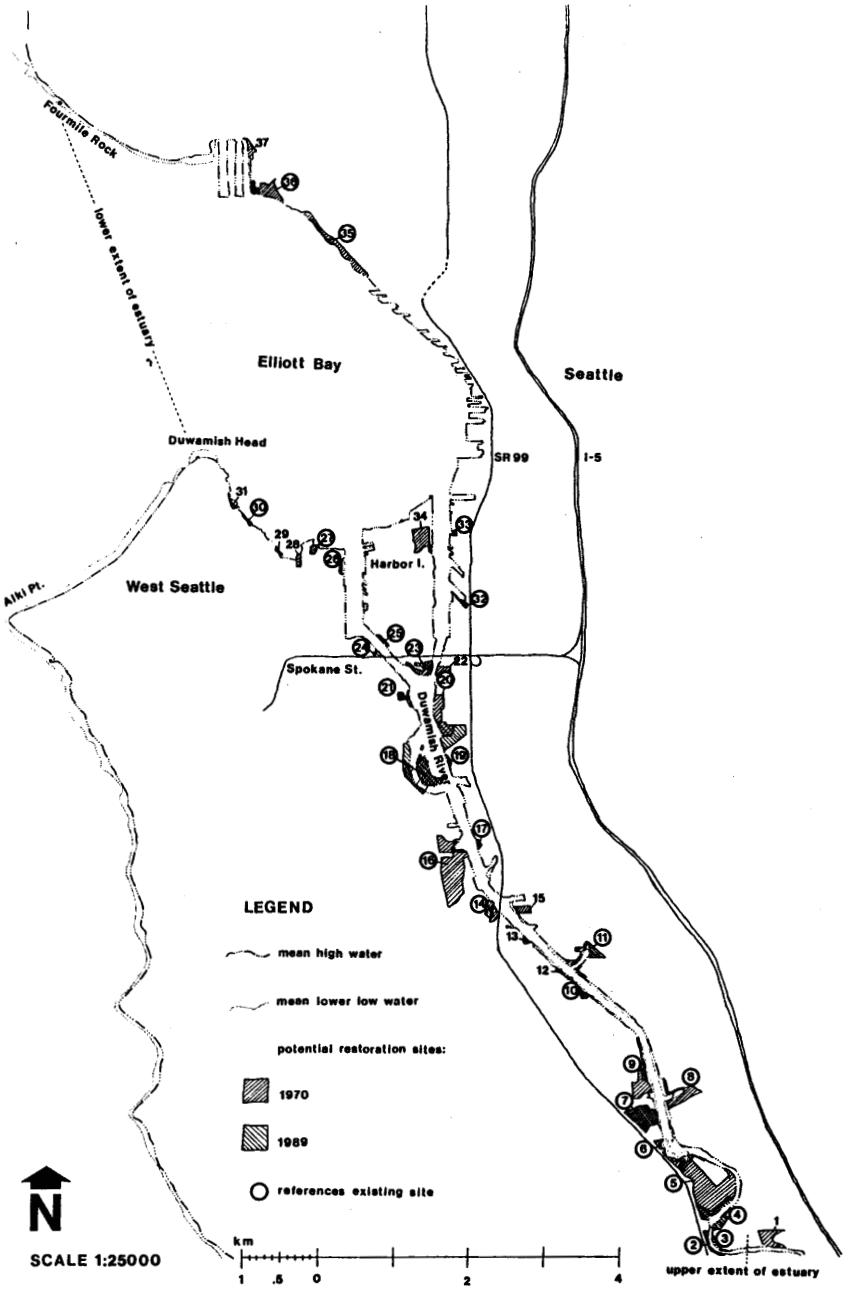

Figure 1.
POTENTIAL WETLAND RESTORATION SITES IN THE DUWAMISH RIVER ESTUARY, 1970 AND 1989.

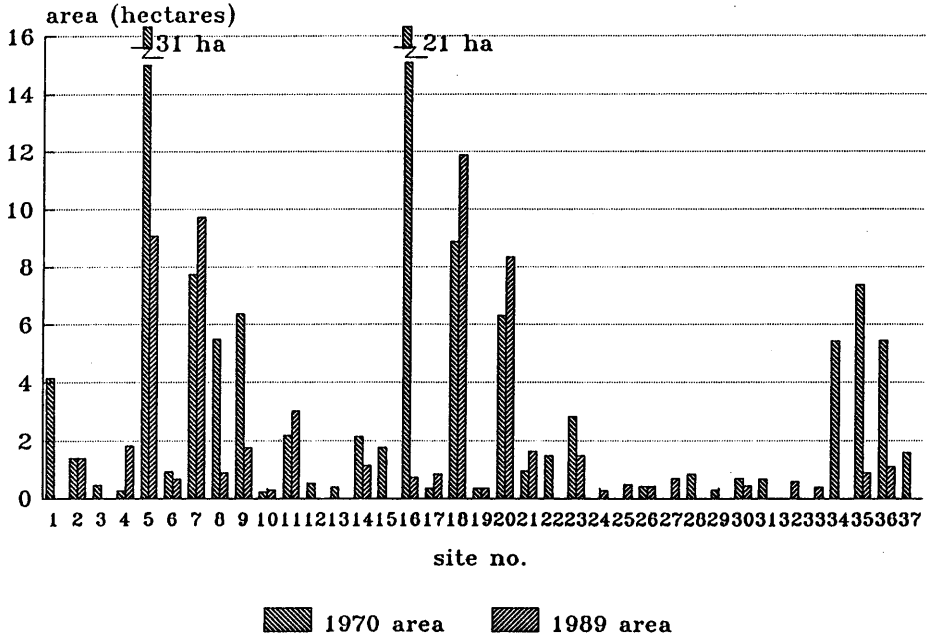

Figure 2.
COMPARISON OF 1970 AND 1989 POTENTIAL RESTORATION SITES AREAS. *Refer to Figure 1 for location of sites.*

Discussion

In addition to a continued loss of wetland area and function, we are also losing potential restoration opportunities to development. Over the past 20 years, 50% of the area that might have been available to restore lost wetlands in the Duwamish River estuary has been developed, further constraining future options to enhance this degrading system. In 1989, Blomberg et al. documented the historical loss of wetlands in the estuary. If potential restoration sites that existed in 1970 had been converted to their historic wetland type, some of these losses could have been recovered; in 1989 much less could have been regained (Figure 3). And while the consideration of smaller sites and under-utilized developed parcels might increase the available pool of alternatives, site-specific constraints may serve to eliminate several of the currently available options (Table 1).

MECHANISMS FOR IMPLEMENTING RESTORATION PROJECTS

While a strong case for the need and opportunity to restore degraded estuarine function exists, implementation remains an important question. A variety of

Table 1
AVAILABLE INFORMATION FOR POTENTIAL RESTORATION SITES.

Site	Location	Site Descriptive Information				Potential Site Benefits		Potential Site Detriments	
		Area	Shore	Ownership	Historic w.l.	Proximity to	Proximity to	Contaminant	Long-term
		(ha)	(m)		type	other wetlands	upland habitats	Sources	Dev. Plans
2	Marginal Pl. S.	6.5	1435	Boeing	tidal swamp			?	
	@ S. 110th								
4	Pacific Hwy. S.	1.8	371		tidal swamp			?	
	@ S. 113th								
5	Turning Basin No. 3	2.6	1128	POS	tidal swamp			?	
6	Marginal Pl. S.	0.7	97						
	@ S. 100th								
7	Marginal Pl. S.	9.7	194	City Light	tidal swamp				
	@ S. 96th								
8	Slip No. 6	0.9	449		tidal swamp			outfall	
9	18th Av. S.	1.8	550		tidal swamp			outfall	
	@ S. 92nd								
10	10 Av. S.	0.3	55	City of Sea.	tidal swamp				none
	@ S. Kenyon			Parks Dept.					
11	Slip No. 4	3.0	639		tidal marsh			outfal/	
								toxic hot spot	
14	1st Av. SW @	1.2	53		tidal marsh		.5 km to gr.belt	outfall	
	SW Peninsula Pl.								
16	T-115	0.7	273	POS	river channel		.25 km to gr.belt	outfall	
17	S. Fidalgo St.	0.9	440		river channel		.5 km to gr.belt		
	@ Ohio Av. S.								
18	T-107/Kellogg I.	11.9	2180	POS	tidal marsh	intertidal w.l.	adj. to gr.belt		designated
						on N end of I.			conservancy
19	GAO Property	0.3	206	Fed. Gov't	tidal marsh		adj. to T-108 mit	outfal/	
				(GAO)			proj.; Kellogg I.	toxic hot spot	
20	T-108/	8.3	413	POS	tidal marsh/		adj. to T-108 mit	outfall	
	Diagonal Av. S				tidal flat		proj.; Kellogg I.		
21	T-105: Marginal Wy.	1.6	241	POS	tidal flat	.75 km to	.25 km to gr.belt	outfall	
	SW @ SW Dakota					Kellogg I.			
23	T-102: 11th Av. SW	1.5	117	POS	tidal flat		.5 km to gr.belt		
	@ SW Manning								
24	Marginal Wy. SW	0.3	44		tidal flat		.25 km to gr.belt		
	@ SW Spokane								
25	Harbor I.: Klickitat Av.	0.5	194		tidal flat		.25 km to gr.belt	outfall	
	SW @ SW Hanford								
26	SW Florida St.	0.4	151						
27	Pier 2	0.7	70	POS	shallow	.5 km to fr. wtr.	.5 km to gr.belt	toxic hot spot	
					subtidal	wetland			
30	Seacrest Marina	0.4	227		tidal flat		adj. to gr.belt	outfall	
32	Pier 27	0.6	187	POS	tidal flat			outfall	
33	T-30	0.4	70	POS	tidal flat			outfall	
35	Myrtle Edwards Pk.	0.9	1259	City of Sea.	tidal flat		adj. kelp beds	outfall	none
				Parks Dept.					
36	Pier 89	1.1	224	POS	tidal flat		adj. kelp beds		
							.5 km to tidal flat		

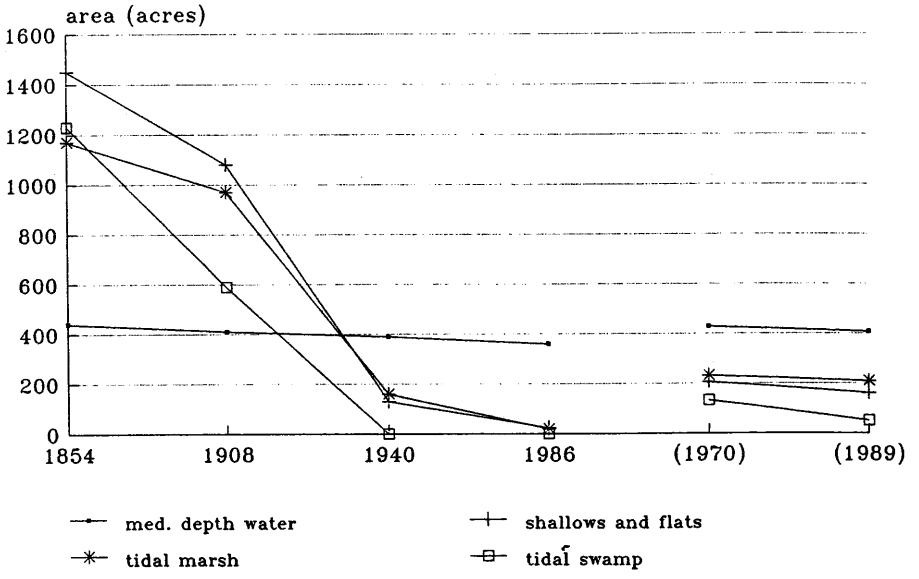

Figure 3.
***CHANGE IN WETLAND AREA** (left side of graph, from Blomberg et al., 1988) and restoration potential (right side).*

resource agency programs currently include elements that could be utilized in undertaking wetland restoration projects that would individually contribute to a system-wide restoration strategy.

Puget Sound Water Quality Authority (PSWQA) Management Plan

Element W-8 of the 1991 plan calls for an interagency effort to develop a pilot restoration program for several specific wetland sites in Puget Sound. This would provide early action "gear up" for the more extensive restoration program detailed in W-8. Consideration should be given to utilize these pilot efforts to coordinate and assist in designing and initiating system restoration.

U.S. Environmental Protection Agency (EPA) Wetlands Action Plan

In describing the federal role in participating in wetlands planning processes, emphasis is placed on the importance of cross-boundary considerations and valuable and/or threatened systems (U.S. EPA, 1989). Advance planning provides the context for coordinating actions among agencies and considering the cumulative effects of wetland loss and degradation within particular geographic areas. This information can then be factored into decisions regarding permits and mitigation requirements, and in identifying areas for acquisition or restoration. It is anticipated that EPA will provide guidance, technical assistance and support to enhance the role of the state and local

governments in both regulatory and non-regulatory wetlands protection efforts. Furthermore, EPA will identify opportunities and initiate projects to restore and create wetlands to increase the quantity and quality of wetlands and to meet national environmental goals. Through its participation in advanced identification and other advance planning processes, EPA will encourage and assist in identifying potential sites for restoring wetlands. EPA will consider the cumulative impacts of wetland losses within that watershed when making these recommendations.

U.S. Fish and Wildlife Service (FWS) Washington State Wetlands and Riparian Initiative

The overall goal of this initiative is to protect, restore and enhance the wetland and riparian resources and associated upland habitats in the state of Washington (U.S.F&WS, 1990). To meet the objectives of this initiative, FWS recommends that it: "assist counties and local governments in the delineation of wetlands, the identification of opportunities for wetland acquisition, enhancement, and restoration; the assessment of wetlands for acquisition; and comprehensive wetland planning; encourage local sponsors of flood control projects to construct setback levees to avoid damage to streamside corridors; encourage the Corps to remove their standards requiring that federal and non-federal flood control levees be maintained free of trees and shrubs; and engage in additional wetlands restoration projects through cooperative agreements with private landholders".

The U.S. Army Corps of Engineers (Corps) and the National Estuary Program

In describing their intent in participating in the National Estuary Program (U.S. Army Corps, 1990), the Corps states that a "team approach by all agencies involved, utilizing all of the resources they have available, is a requisite for the success of the program." The Corps has investigated and has broad experience in the construction and restoration of wetlands and other fish and wildlife habitats. Additionally, their investigations in environmentally beneficial uses for dredged material is a valuable asset. The Corps has authority and interest to cooperate with states in the preparation of plans for water resources development and conservation. States can request planning assistance from the Corps in their priority watersheds and estuarine areas. The Corps has stated that such interaction could provide a useful adjunct to a comprehensive estuary plan, such as the Puget Sound estuary plan (U.S. Army Corps, 1990). In the Duwamish River estuary, the Corps conducts routine maintenance dredging and maintains a large settling basin for clean sediment at the head of navigation. The general area near the head of navigation represents one of the largest and most versatile potential restoration sites (see Figure 1 and Table 1, site 5) in the system. An important opportunity exists to use this area as a multi-objective settling basin, habitat complex, and public access and viewing area.

Natural Resource Trustees

Under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) as well as the Clean Water Act, the National Oceanic and Atmospheric Administration (NOAA), in cooperation with the FWS, tribes, and state resource agencies, has responsibilities as a Natural Resource Trustee. Under these Acts, NOAA is responsible for living and non-living natural resources in coastal and marine areas. These include all life stages, wherever they occur, of anadromous fishery resources, as well as tidal wetlands and other ecosystems which support these living marine resources. CERCLA charges NOAA with the responsibility to investigate resource damages, negotiate compensation for damages, and oversee restoration activities.

Port of Seattle Long-term Development Plans

Under the City of Seattle Shoreline Master Plan, the Port of Seattle has outstanding obligations to provide public access amenities. Fulfillment of these responsibilities could be envisioned to include provision of intertidal habitat. Additionally, the Port, anticipating continued increases in demand for its container terminal facilities, estimates that as much as 130-295 acres of additional space may be needed by the year 2000. These demands for expansion will undoubtedly require intertidal filling and habitat loss, and thus mitigation projects. The Port might be expected to act cooperatively with resource agencies, receiving mitigation credit for it's investment in restoration projects, while agencies contribute resources to enhance projects or realize project potential beyond that for which the Port is liable.

Other Local Interests

The Muckleshoot Tribe has both economic and tribal stewardship interests in the ecological function of the Duwamish River estuary. The City of Seattle, King County and Washington State Department of Natural Resources all own shorelands or subtidal lands within the lower Duwamish. These government institutions all have public stewardship responsibilities and therefore an obligation to preserve important wetland functions. Local community groups, the City, and Washington Department of Fisheries have demonstrated interest in restoring ecological function in Longfellow Creek (Puget Sound Cooperative River Basin Team, 1990). This creek corridor contains almost one-third of the remaining open space within the city. Clearly, coordinated restoration activities in these adjacent systems would be mutually beneficial.

CONCLUSIONS

In establishing goals of no net loss and ultimate gains in wetland resources, we have created a need for new approaches and perspectives. No longer can we expect regulation of development to provide all of the answers. Public agen-

cies must begin to identify and implement wetland restoration projects. These projects should be selected and designed to enhance and rehabilitate damaged systems in order to provide important wetland functions. Furthermore, it is insufficient to view these projects in isolation. Implementation must be carried out within a system-wide restoration plan that seeks to coordinate mitigation projects and non-compensatory restoration projects. Furthermore, these projects and the activities of various agencies must be coordinated to maximize investments.

While it may be necessary to adopt a system-wide perspective if wetland functions are to be preserved in the Duwamish River estuary, opportunities to do so are decreasing. Over the past 19 years, the number of undeveloped shorefront parcels has decreased, as has the average size of these sites. With these declines, opportunities for locating restoration projects have become increasingly constrained. Options can only be expected to decrease as urbanization encroaches upon and destroys the few remaining opportunities. Government agencies should act now to seize remaining opportunities, integrating wetland restoration into their current programs.

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RESTORATION OF THE SALMON RIVER SALT MARSHES: RETROSPECT AND PROSPECT

Robert E. Frenkel[1]

INTRODUCTION

More than a third of Pacific Northwest wetlands have been lost in this century, 31% in Washington and 38% in Oregon (Dahl, 1990). Close to ports and population, coastal salt marshes have been more heavily impacted than most wetland types, with loses in individual estuaries commonly between 50% and 95% (Boule and Bierly, 1987). As wetland habitat diminishes, dependent organisms vanish and important ecological services like flood protection and water quality enhancement are depleted. To stem and possibly reverse these historic trends, a program of restoring degraded wetlands or creating new wetlands has been advanced (National Wetlands Policy Forum, 1988; Kusler and Kentula, 1990).

"...[R]estoration refers to the reestablishment of a wetland in an area where it historically existed but which now performs no or few wetland functions" (Kruczynski, 1990). It is a common form of compensatory mitigation and is distinct from wetland creation which attempts to establish a wetland at a site which was not a wetland in the past. An assumption of mitigation policies is that the degraded site can be restored to its pre-impact condition; however, on the Pacific Coast there is more uncertainty than knowledge in attempts at ecological restoration (Josselyn et al., 1990).

An unusual opportunity presented itself to further our knowledge of salt marsh restoration when in 1974 Congress established the Cascade Head Scenic Research Area straddling the Salmon River estuary. The U.S Forest Service administers the scenic research area in which one long-term goal is the "...revitalization and restoration of the Salmon River estuary and its associated wetlands to a functioning estuarine system free from the influences of man" (U.S. Forest Service, 1976). In 1978, about 75% of the Salmon River salt marshes had been historically isolated from estuarine circulation by dikes. The specific objective of the Forest Service is to redevelop pristine estuarine conditions which, for diked pasture, is high salt marsh dominated by tufted hairgrass (*Deschampsia caespitosa*) and dissected by deep sinuous tidal creeks. The Forest Service acquired 32 ha of diked farmland on the north shore and, in early September 1978, partially removed about 640 m of dike. No planting took place.

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From 1977 to 1980, Diane Mitchell (1981) collected baseline data in the diked pasture and flanking "intact" high marsh control sites, established an intensive sampling system of permanent plots, and analyzed initial restoration changes. In 1988, Janet Morlan and I thoroughly reexamined restoration progress. My first purpose in this paper is to summarize progress in restoring the 21 ha pasture to original salt marsh composition, structure, and function eleven years after dike removal. Second, I comment on what we have learned and on prospects for complete restoration.

RETROSPECT

The pasture was created in 1961 by enclosing high salt marsh behind dikes fitted with a tide gate. Two relatively unaltered flanking high salt marshes, each about 6 ha, served as controls against which changes in the restoring marsh could be measured. Restoration was monitored at 115, 1 m^2 permanent plots along 20 transects and 450, 0.1 m^2 temporary plots prior to dike breaching in 1978 and after dike removal in 1979, 1980,1981, 1982, 1984, and 1988. Peak biomass was harvested at permanent plots and elevations tied to both NGVD and a tide station were surveyed in 1978, 1979 and 1988. Samples were collected at permanent plots for soil texture, interstitial soil-water salinity, organic matter, and accretion above a sand tag laid in 1978. Elevational and vegetational cross-sections of eight tidal creeks were also surveyed.

Composition

Species composition changed radically over the restoration period (Figure 1). Upland pasture species were immediately killed or heavily stressed upon intrusion of salt water. Pacific silverweed (*Potentilla pacifica*) and creeping bentgrass (*Agrostis alba*), prominent pasture plants, remained as residuals but diminished in importance in the developing marsh over 11 years of restoration. Unvegetated soil was most extensive (ca. 40% cover) in the second year after breaching and, by the sixth year (1984), was again negligible. Ephemeral colonizers such as brass buttons (*Cotula coronopifolia*) established themselves in the first and second year after dike removal, but disappeared by 1984. Lyngbye sedge (*Carex lyngbyei*), pickleweed (*Salicornia virginica*), saltgrass (*Distichlis spicata*) and Baltic rush (*Juncus balticus*) were important colonizers that, by 1988, characterized and dominated many of the developing salt marsh communities. Species composition in the flanking control areas changed little.

With the immediate destruction of three generalized pasture plant communities in 1978, salt marsh assemblages began to develop and by 1988 could be generalized by five marsh communities or community groups. A low elevation, nearly monotypic Lyngbye sedge community occupied the upriver two-thirds of the site. Much of the remaining downriver one-third was

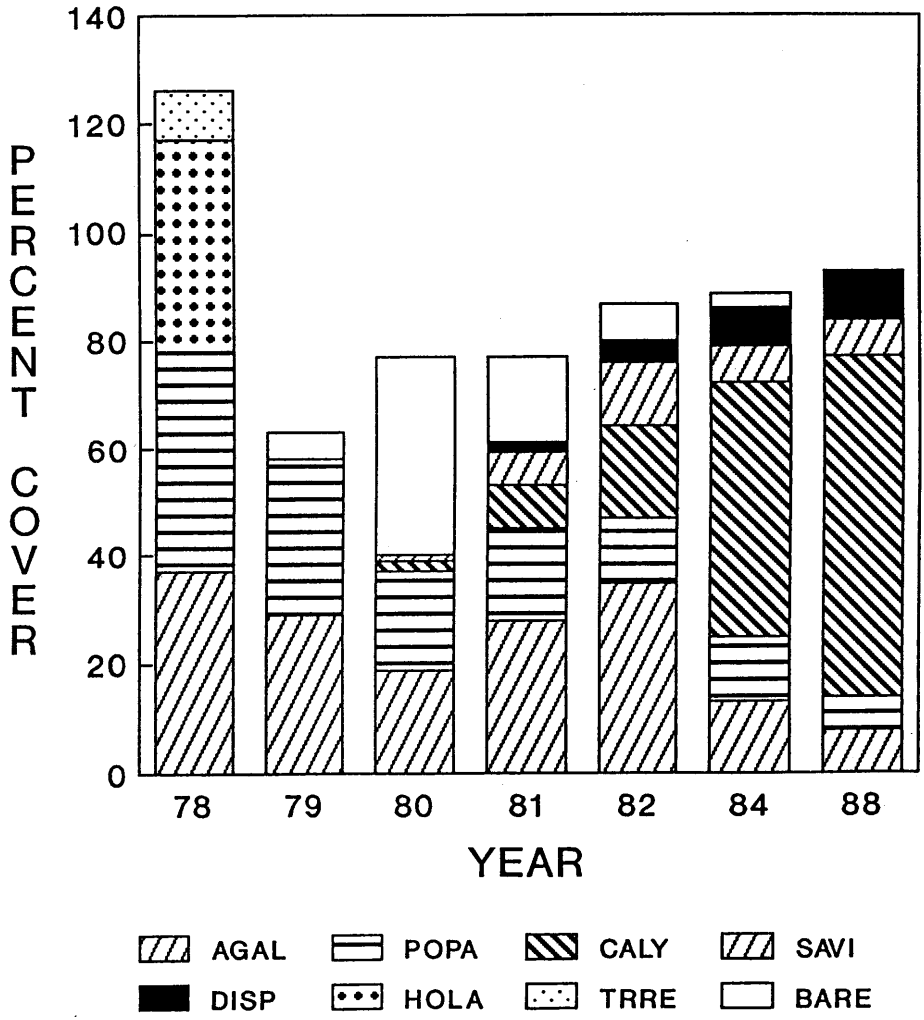

Figure 1.
PERCENT COVER OF SELECTED SPECIES AND BARE GROUND FROM PASTURE IN 1978 TO RESTORED SALT MARSH IN 1988 IN THE SALMON RIVER RESTORATION SITE. *Dike removal occurred in September 1978. Species acronyms are: AGAL =* Agrostis alba, *DISP =* Distichlis spicata, *POPA =* Potentilla pacifica, *HOLA =* Holcus lanatus, *CALY =* Carex lyngbyei, *TRRE =* Trifolium repens, *SAVI =* Salicornia virginica, *BARE = unvegetated bare ground.*

dominated by a low elevation pickleweed-saltgrass community. The upland margin of the site was marked by communities with Lyngbye sedge, creeping bentgrass, Pacific silverweed, and Baltic rush. Plant communities in the restored marsh were characteristic of low salt marshes and did not resemble the usual high marsh communities with tufted hairgrass, Pacific silverweed, and Baltic rush typical of the flanking controls (Table 1).

Structure

Surface elevation, the primary control on marsh hydrology, composition and function, was on the average 34.9 cm lower in 1988 in the restored area than in the flanking controls. The lower elevation followed 17 years of diking and associated subsidence. The most depressed areas were dominated by sedge or pickleweed-saltgrass communities (Figure 2). The minimum elevation at which high marsh tufted hairgrass or Pacific silverweed communities developed were on former dikes, which were 15-25 cm above the present low marsh in the restored area. Measurements above 1978-laid sand tags indicated that the lowest elevations in the restored marsh increased in elevation at a greater rate (8-10 cm per decade) than the higher elevations in the site (3-7 cm per decade). Elevation increases are hypothesized as being caused by a combination of sedimentation and increase in buoyancy.

Table 1.
PLANT COMMUNITIES, GENERALIZED TIDAL POSITION AND PERCENTAGE OCCURRENCE IN THE SALMON RIVER RESTORED MARSH AND ADJACENT CONTROLS IN 1988 BASED ON 450 PLOTS.

Community	Tidal Position	Percent Occurrence	
		Restored	Control
Carex lyngbyei	Intertidal	100	0
Salicornia virginica-Distichlis spicata	Intertidal	76	24
Carex lyngbyei-Potentilla pacifica	Middle	93	7
Agrostis alba-Potentilla pacifica	Middle	90	10
Potentilla pacifica-Juncus balticus	High	41	59
Juncus balticus-Deschampsia caespitosa	High	13	87
Oenanthe sarmentosa-Potentilla pacifica	Extratidal	0	100
Oenanthe sarmentosa-Scirpus microcarpus	Extratidal	0	100

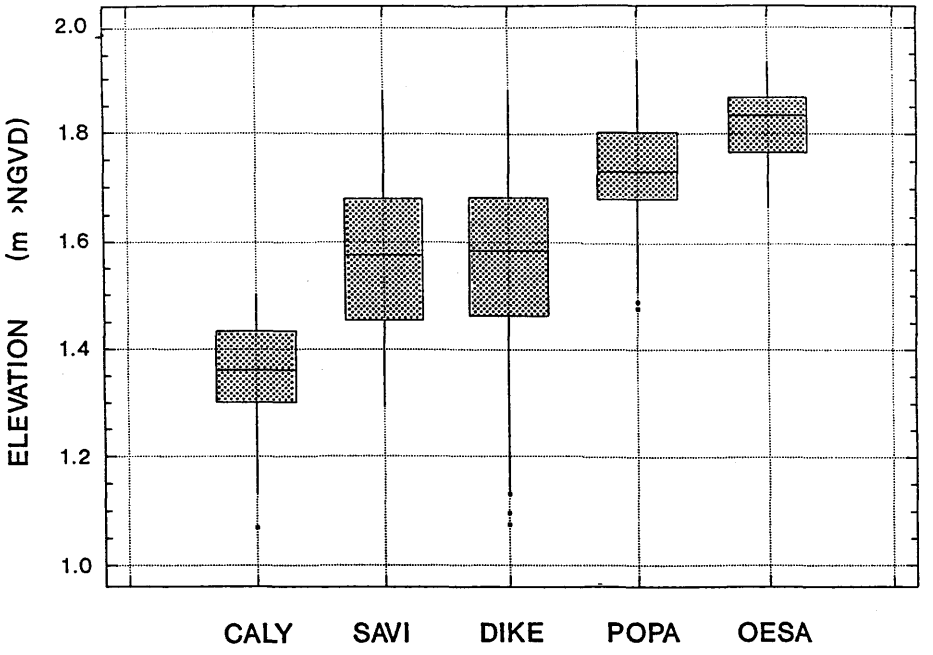

Figure 2.
STATISTICAL DISTRIBUTION OF FOUR PLANT COMMUNITIES, COMMUNITY GROUPS, AND LEVELED DIKES IN THE SALMON RIVER RESTORATION SITE IN 1988. *CALY* = Carex lyngbyei *comm., SAVI* = Salicornia virginica-Distichlis spicata *comm., POPA* = Potentilla pacifica *comm. groups (wet and dry phase), OESA* = Oenanthe sarmentosa *comm. groups at upper margin of control site, DIKE = leveled dikes dominated by* Deschampsia caespitosa *comm.*

Sediments accreted at a mean rate of 3.6 cm (sd=1.44, se=0.22) per decade as measured in cores taken above 1978 sand tags. Maximum accretion was at the lowest elevations, especially in areas dominated by sedge. Although salinities were measured in September (expected maximum), plant species and soil salinities correlated as anticipated (Hutchinson 1990). Sedge had a significant negative correlation (r_s=-0.39, p=0.005) with lower salinities in contrast with positive correlations for pickleweed (r_s=0.58, p=0.000) and saltgrass (r_s=0.64, p=0.000). Sandier substrates downriver were significantly related to more saline conditions and cover of pickleweed (r_s=0.48, p=0.001) and saltgrass (r_s=0.56, p=0.000).

Without function while diked, former tidal creeks filled in. Upon tidal reconnection, vestigial creeks deepened and narrowed under daily pulses of tide. Typically, creeks deepened between 20 and 60 cm over eleven years of restoration.

Function

Biomass and primary productivity are often regarded as important functional aspects of ecosystems (Odum, 1971). Primary productivity was estimated from peak biomass harvest based on the method of Kibby et al. (1980). Estimates of above ground net primary productivity were about the same in the flanking controls as they were in pre-restoration diked pasture (ca. 1200 g/m^2/yr dry weight) and comparable to, or slightly higher than, other northwest high salt marshes (Hutchinson, 1986). Eleven years after dike removal, net primary productivity almost doubled in the restored marsh (2300 g/m^2/yr dry weight), representing a very high primary productivity. Enhanced productivity in the restoring low salt marsh is hypothesized as being caused by tidal-borne nutrients and by nutrient releases from decomposing organic matter, in addition to diminished competition following pasture species mortality.

LESSONS AND PROSPECTS

Eleven years of monitoring have provided us with important guidance. Among lessons learned are the following:

- Reinstating complete hydrological connection with the estuary is critical to the success of salt marsh restoration. In salt marshes, creek systems are critical to water circulation and must be reestablished.
- Knowing the surface elevation of the restored site is absolutely essential. A precise elevation survey tied to a tidal datum is a crucial element in restoration design. Evaluation of historic subsidence must be made. Elevation, together with the creek system, controls hydrology.
- Knowledge of soil salinity and texture will help predict restoration direction.
- Planting is probably unnecessary, if sources of local propagules are present.
- Post project monitoring should be continued for at least 10 years to evaluate restoration success.
- A goal of strict in-kind restoration is unrealistic.

The general objective of the U.S. Forest Service in restoring the Salmon River salt marsh had been to return the diked pasture to a functioning ecosystem and ultimately to return the estuary to the state prevailing prior to agricultural alteration. This research demonstrates successful restoration of a diked pasture to a functioning natural salt marsh.

Long term prospects for complete restoration to pristine high salt marsh are more problematic. Elevation largely controls salt marsh character. Since elevations in the restored marsh are about 35 cm lower that the surrounding, high salt marshes, it will take many years for the restored elevations to reach their former levels and for truly pristine vegetation to prevail. In the mean-

time, surrounding natural salt marshes are changing because of sedimentation and altered drainage in the flanking control areas. Future marsh and estuarine character will necessarily reflect a heritage of altered hydrology. Development of high salt marsh, which would be in-kind, in-place restoration, is an unrealistic goal. A more pragmatic general goal is the reestablishment of a naturally functioning salt marsh ecosystem consisting of natural plant communities, not the reestablishment of pristine conditions.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Environmental Protection Agency, Region 10; particular thanks are due to William M. Riley, Chief Water Resources Assessment Section. Diane Mitchell initiated the research and the entire monitoring program could not have taken place without her meticulous work. Janet Morlan provided useful comments on this paper and conducted most of the field and laboratory work being aided in the field by Bob Harmon, Pete Klingeman and many other individuals.

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SEAWEED MANAGEMENT SYSTEMS FOR USE IN HABITAT RESTORATION, ENVIRONMENTAL MANAGEMENT, AND MITIGATION

John E. Merrill and David M. Gillingham [1]

INTRODUCTION

Seaweed beds, especially kelp forests, are exceptionally important biological assemblages in the world's nearshore marine environment, including Puget Sound and the greater northeastern Pacific. We will stress three particularly critical roles that they play in the environment: 1) their importance within the food web as primary producers; 2) the habitat for other organisms created from their three dimensional complexity; and 3) the water purifying effects of their mineral nutrient uptake, carbon dioxide uptake, and oxygen production.

The primary productivity of kelp forests is often very high and can equal that in other, more often cited habitats, such as tropical rain forests (Mann, 1973). The impact of this production stretches throughout the extended food web, supporting not only the direct herbivorous consumers, but also the detrital food chains and virtually all of the successive trophic levels (Duggins, 1988; Duggins, et al., 1989). Even the growth of filter feeding organisms, seemingly removed from the seaweed-based food chain, can be greater in the presence of kelp forests (Duggins, et al., 1989).

In addition to providing food for many organisms, kelp forests provide important habitat for a wide range of fish and shellfish, both juvenile and adult (Holbrook, et al., 1990; Carr, 1989; Duggins, 1988; Leaman, 1980; Coyer, 1979). Numerous species of birds and marine mammals whose existence and activities are enjoyed by humans rely upon kelp beds and their associated biota.

Seaweeds, through their natural metabolism, provide significant seawater purification. Primary productivity via the photosynthetic processes depends on the uptake of carbon dioxide and the release of oxygen. This oxygen production can significantly offset various causes of oxygen depletion, including animal or fish respiration and waste-caused biological and chemical oxygen demand (B.O.D. and C.O.D.). The complementary uptake of carbon dioxide becomes increasingly important as we recognize the impacts of rising global atmospheric carbon dioxide levels resulting from the combustion of fossil fuels. Large quantities of nitrogen and phosphorus are required for the growth of seaweeds and production of their tissues. Removal of these mineral compounds from the seawater by seaweeds is particularly important in light

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of the increasing problem of marine eutrophication and hypertrophication (for example see Sfriso, et al., 1987).

Although these beneficial properties of seaweeds are widely recognized, naturally occurring seaweed beds are experiencing increasing threats from a variety of sources. Construction of docks, piers, breakwaters and marinas may physically disrupt their habitat. Siltation, caused for example by dredging or erosion through forest clear cuts, can smother young plants or make rock substrata unavailable. High levels of domestic and industrial pollution can result in the decline, disappearance, or alteration of seaweed beds. In addition, pressures may arise for the harvest of some species for food or industrial uses (Cheney and Mumford, 1986; Dethier, et al., 1989).

For these reasons we have developed efficient methods for the artificial planting and maintenance of two important Pacific Northwest kelp species: bull kelp, *Nereocystis luetkeana* (Mertens) Postels & Ruprecht, and giant kelp, *Macrocystis integrifolia* Bory. The methods we use are modified from those used in Asia and elsewhere for the farming of kelp sea vegetables (Druehl, 1988; Kawashima, 1984). In this report we summarize our methods and show representative growth and productivity data.

GENERAL BIOLOGY OF KELP SPECIES

Kelps are members of the brown algae, or Phaeophyceae. They have a biphasic life history comprised of a microscopic sexual phase (gametophyte) that alternates with the large, familiar kelp plant (sporophyte) (Fig. 1). Spores are produced by the sporophyte in special areas on the fronds. These spores germinate to form filamentous male and female gametophyte plants. When the gametophytes are mature, male sperm cells fertilize the eggs to form the next generation of sporophytes.

This life history requires two key considerations for successful planting and maintenance of artificial kelp forests: 1) reliable methods for the artificial production of seedstock, and 2) designs for artificial substrates to allow placement where desired.

Manipulation of these kelp species consists of two relatively distinct stages: seedstock production and field grow-out.

Seedstock Production

Nereocystis spores are borne in discreet "sori" that can be easily separated from the remainder of the frond, whereas *Macrocystis* spores are borne on specialized fronds at the base of the plant called "sporophylls". In either case, ripe spore bearing tissues are identified in the field by their dark brown color and by the presence of a mucilaginous surface feel.

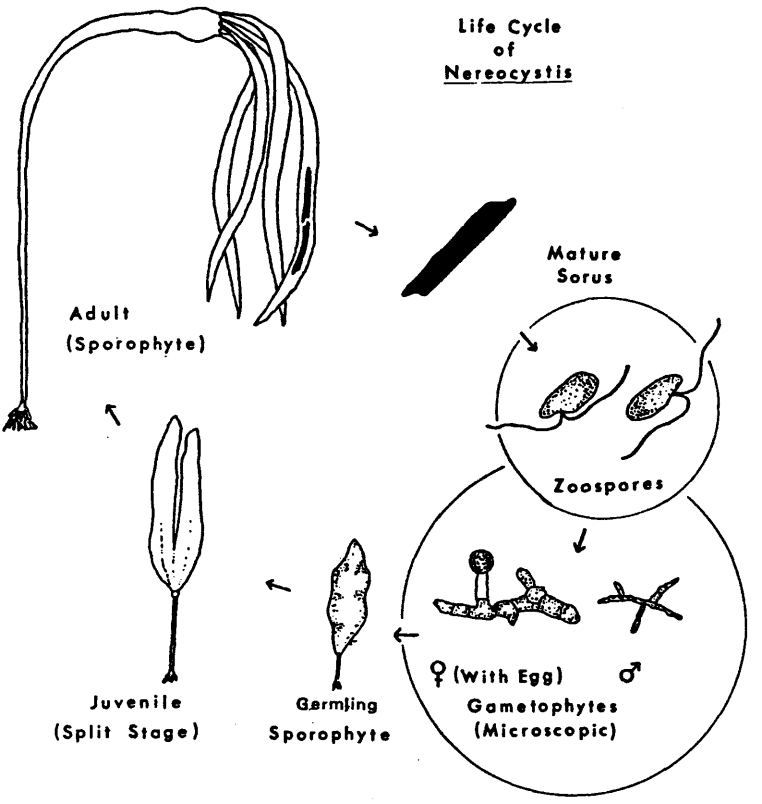

Figure 1.
NEREOCYSTIS LUETKEANA LIFE HISTORY DIAGRAM; *also typical for other kelp species. Familiar kelp plant is sporophyte phase. Spore bearing sori develop as dark patches at distal ends of strap like fronds. Spores release from mature sori give rise to male and female gametophytes. Germination of fertilized eggs result in new sporophytes. Spores and gametophytes are microscopic.*

Careful attention is paid to reducing the possibility of contamination of cultures. All seawater used after tissue collection should be sterilized, and the tissues themselves are thoroughly cleaned and disinfected, as follows: selected sori or sporophylls are gently scrubbed with tissue paper, then surface disinfected with a dilute iodine solution followed by careful rinsing in sterile seawater. The spore bearing tissues are then layered between barely-moist paper towels and transported on ice to the culture facility. If the material is completely ripe a synchronous release of spores will occur when it is reimmersed in seawater. Less ripe tissue can be induced to release spores by overnight storage at 4°C followed by reimmersion. Initial spore density is determined via microscopic cell counts utilizing a hemocytometer. Spore

density is adjusted by dilution with sterile seawater to a final inoculation density of 1-5 X 10^3 cells•ml^{-1}.

A suitable substrate for seedstock production is #12 white braided nylon seine twine. Twine is wrapped on suitable spools or frames and pretreated by an overnight soak in a solution of sodium carbonate at 50-100g per 20 liter volume, followed by several rinses in distilled water. Prepared twines are immersed in the spore suspension and allowed to incubate overnight with gentle aeration. The following day the twines are moved to the culture vessel (Fig. 2) containing fresh sterile seawater enriched with Guillard's f nutrient enrichment (Fritz Aquaculture, Dallas, Texas). Cultures are maintained at 10-12°C and 80-100$\mu E \cdot m^{-2} \cdot s^{-1}$ cool white fluorescent light. The seawater medium is agitated with gentle aeration and is exchanged at 10 day intervals.

Growth and maturation of gametophytes takes 10-20 days, after which time young sporophytes will be visible on microscopic examination. After 3-4 weeks the twines are ready for field deployment.

FIELD GROW-OUT

Care is required in transporting the seed-twines from the laboratory to the field site in order to avoid excessive temperatures or light intensities, as either can be detrimental to the viability of the juvenile kelp plants.

Seed-twines are typically deployed in the field by attaching them to a larger diameter rope, or long-line, that is anchored at appropriate depths (Fig. 3). The arrangement and placement of such long-lines can be designed to fit a wide range of site requirements. An example for a large 1-acre unit is shown in Figure 4.

A critical aspect in manipulating the growth of kelp plants is the depth at which the long-lines are deployed. In nature the distribution and seasonality of these kelps are determined in part by the availability of sufficient light (Vadas, 1972; Foreman, 1984). We have found most rapid growth when long-lines are deployed at 1-2 meters below the surface, apparently due to this light limitation. Furthermore, we are able to overcome the strong seasonality of *Nereocystis* by manipulating this factor. We have achieved good growth and development of this species at all seasons of the year, even though in nature it is predominantly a summer-fall plant. Development of plants can be greatly accelerated by careful management and adjustment of depth through the growth cycle.

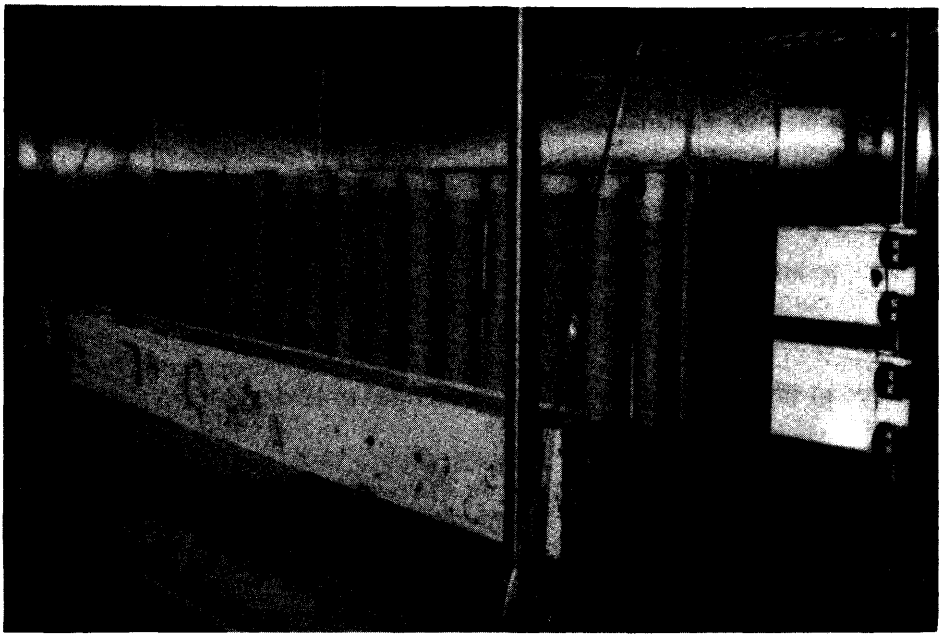

Figure 2.
CONTROLLED PRODUCTION OF KELP SEEDSTOCK. *Nylon twine is wrapped on tubular spools and inoculated with spores from field collected spore-bearing tissues. Seed twines are incubated in sterile, nutrient-enriched seawater for 4-6 weeks. Juvenile kelp plants first appear after 2-3 weeks. Culture chamber shown contains 14 spools, each with sufficient twine to seed 50 meters of long-line. Chamber is constructed from clear acrylic plastic ("Plexiglas" tm) and contains approximately 50 liters of culture medium.*

RESULTS

We have achieved very reliable production of both *Macrocystis* and *Nereocystis* populations by these methods. An example of the growth of *Nereocystis* is shown in Figure 5. We have measured crop densities of 3-5 kg per meter of long-line 110 days after seeding and up to 21.5 kg per meter after 135 days (approximately 32 tons per acre). *Macrocystis* plants develop somewhat more slowly (Fig. 6), however they can develop greater standing biomass because of their longer growth cycle and perennial habit.

We have successfully maintained *Macrocystis* long-lines for two years; however, we have not yet determined an average long-line life expectancy. One potential problem can arise as populations of sea urchins and other grazers populate the plants and cause significant damage. Specific episodes of settlement of fouling organisms such as barnacles and bryozoans seem to be site

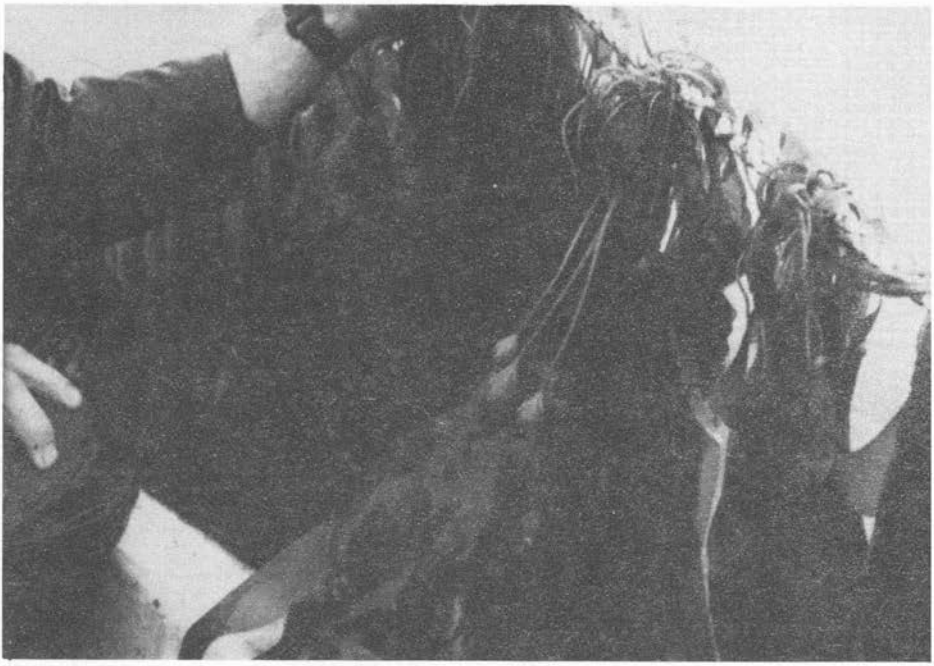

Figure 3.
EXAMPLE OF LONG-LINE ROPE WITH IMMATURE BULL KELP PLANTS AT APPROXIMATELY 110 DAYS OF AGE. *Crop density at this stage measured at approximately 3-5 kg per meter of long-line.*

related and seasonal. The ability of *Macrocystis* to produce new fronds from the basal rhizome allows older, seriously fouled fronds to be cut from the long-line to be replaced by new growth.

The potential value of such artificial plantings has been demonstrated by the numbers and diversity of fish that we routinely observe in and around the kelp long-lines. We have identified perch, kelp greenling, grouper, and other species. Each year during the fall season we observe large numbers of salmon smolt that feed upon amphipods and other small crustaceans that are always present in high densities on the system. During our frequent presence, we have observed sea lions, seals, blue herons, seagulls and a bald eagle feeding in and around our kelp plantings.

With regard to nutrient uptake by kelps as a countermeasure against eutrophication, we have calculated annual uptake of about 530 g N per acre per day by *Nereocystis* (3% N by dry weight).

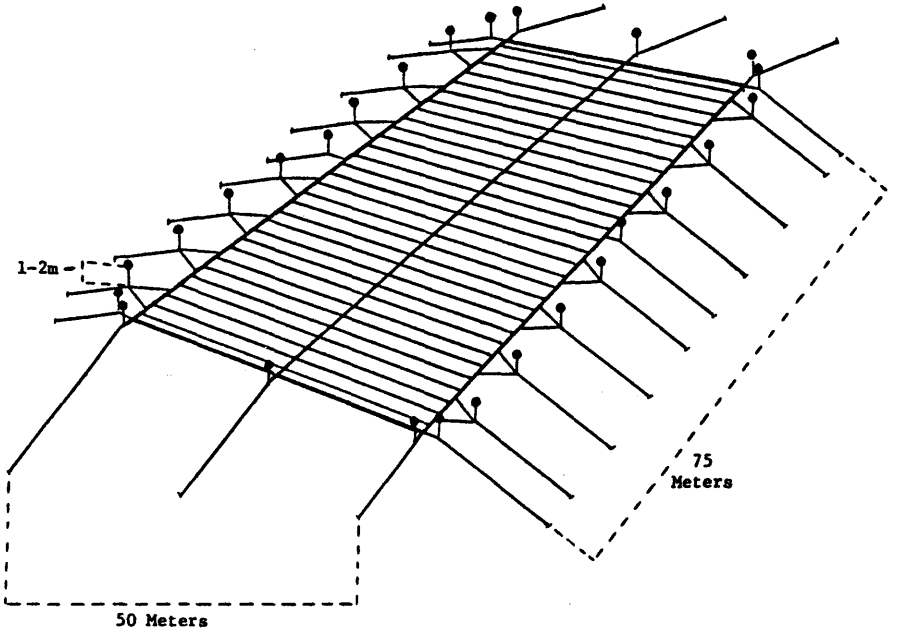

Figure 4.
SET DESIGN FOR KELP DEPLOYMENT. *Total surface area of set, including floats, is approximately 1 acre. Design shows 30 long lines each 50 meters in length. Depth of entire set can be controlled by manipulating the lengths of the float lines. Anchor lines not drawn to scale; typical anchor lines have 5:1 scope (length:depth). Units as small as 1 long-line are easily designed and deployed.*

SUMMARY

We have developed simple and reliable methods for the artificial planting and maintenance of *Nereocystis* and *Macrocystis* kelp forests. Small or large areas can be planted with flexible long-line substrate. We believe that these methods can be widely applied for the purposes of enhancement of marine habitat, remediation of mineral eutrophication, and environmental mitigation. Rapid results are obtainable, thus potentially providing a way to quickly replace critical habitat lost to natural or man-induced disaster.

We have emphasized plantings on artificial substrates such as rope. We also believe that natural or artificial rock substrate can be seeded with kelp either through the direct application of seed-twines, or through secondary settlement from spores released by long-line populations.

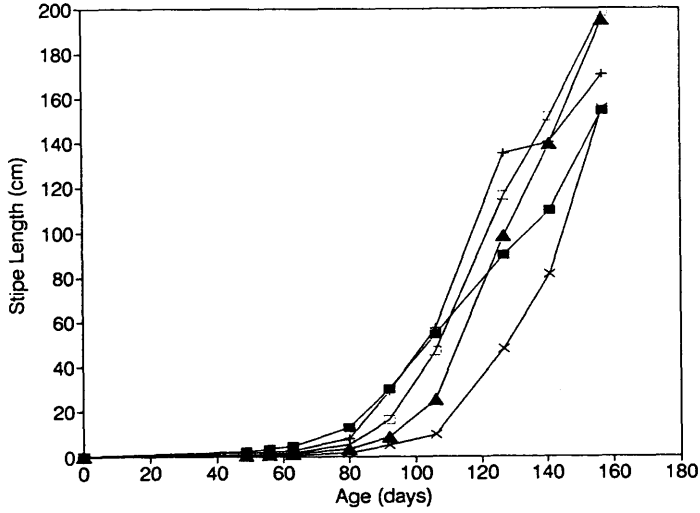

Figure 5.
EXAMPLE GROWTH OF BULL KELP (NEREOCYSTIS); STIPE LENGTH VS. AGE.
Data shown are from Port Gamble November 1988 through April 1989; average of 10 largest plants at each depth interval. ■ 1m, + 2m, □ 3m, ▲ 4m, X 5m. Note that for juvenile plants, shallower plants grow faster due to higher light levels, deeper plants eventually overtake shallow plants as shallow plants discontinue growth at the surface.

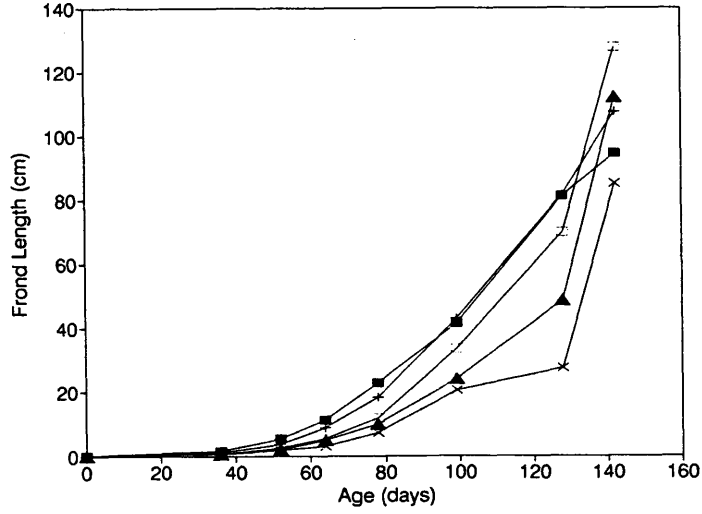

Figure 6.
EXAMPLE GROWTH OF GIANT KELP (MACROCYSTIS); FROND LENGTH VS. AGE.
Data from Port Gamble, December 1988 through May 1989; average of 10 largest plants at each depth interval. ■ 1m, + 2m, □ 3m, ▲ 4m, X 5m. Growth is slower than for bull kelp, but plants are longer lived and may continue to elongate even after reaching the water surface.

The methods presented are specifically for bull kelp and giant kelp; however, they are generally applicable to other kelp species, for example *Laminaria*, *Cymathere*, or *Alaria*, with only minor modifications.

Size constraints in the preparation of this report necessarily limit us to presentation of only a brief overview. A detailed treatment of our methods is in preparation and will be published elsewhere (Merrill and Gillingham, in preparation).

ACKNOWLEDGEMENTS

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PUGET SOUND

RESEARCH '91

MEASURING PUGET SOUND-II

Session Chair:

Andrea E. Copping, Puget Sound Water Quality Authority

INTRODUCTION

Andrea E. Copping[1]

In the session, MEASURING PUGET SOUND-I, we heard seven papers describing the Puget Sound Ambient Monitoring Program (PSAMP) and presenting some early monitoring results. PSAMP is the largest coordinated program presently measuring Puget Sound.

Historically there have been, and continue to be, many other programs and projects which collect information and measurements in the Sound. Most of these studies have been carried out to meet specific objectives. The objectives range from the very large scale questions to localized development project needs. The range includes: the global question of the status and trends of Puget Sound resources, as in the NOAA MESA study in the early 1980s; the need to determine sediment quality at proposed open water dredged material disposal sites like the PSDDA baseline studies; the need to develop specialized tools and methods to better measure the environment; and characterization and monitoring of a wetland created to mitigate a shoreline development project.

Each of these types of studies makes a necessary contribution to the fabric that is our understanding of Puget Sound. Each fills in a different level and detail of information.

In this session we will hear six papers. They will deal with the status of Puget Sound bird and marine mammal populations and threats to those populations; monitoring of the sediment cap over the first open water contaminated sediment capping project in the Sound; long-term trends in Puget Sound fish populations; and the development and acceptance of uniform protocols for measuring Puget Sound. These six papers are nicely representative of the universe of Puget Sound studies. They cover the gamut of information collected by researchers, volunteer monitors, agency staff, and consultants, and seek to answer large scale as well as project-specific questions.

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THE PUGET SOUND PROTOCOLS AND GUIDELINES: TRIALS AND JUBILATIONS

Jacques M. Faigenblum[1], *John W. Armstrong*[2] *and D. Scott Becker*[3]

INTRODUCTION

The background of the development of the Puget Sound Protocols and Guidelines (PSP&G) has been previously described in Armstrong and Becker (1988). The purpose of this paper is to report the progress that has been made with the PSP&G since 1988 and the major issues that have surfaced.

The Need for Protocols and Guidelines

The usefulness of environmental data can be increased if data, collected by a spectrum of different investigators, are directly comparable. If this condition is met, information from different studies can be combined and the spatial and time coverage of local databases can be enlarged to provide a more comprehensive evaluation of environmental conditions. Without comprehensive and integrated databases, environmental managers are left with a patchwork of data sets that may be of limited value for making decisions.

Although protocols exist for a variety of laboratory analyses, sufficient latitude often exists both within and between these protocols to produce data that are not comparable among studies. With respect to field collection procedures, few widely accepted and formally standardized protocols or guidelines exist, yet these collection procedures can substantially influence the results of subsequent laboratory analyses and thus raise the issue of comparability.

One way to increase the likelihood that data collected by different studies in Puget Sound are comparable is to encourage all investigators to use the same sampling, analytical, data quality and data handling methods whenever possible.

Considerations for Development of the Puget Sound Protocols and Guidelines

Environmental variables in Puget Sound have been, and continue to be, measured by a wide variety of organizations: federal, tribal, state and local government agencies, industry, universities and private institutions. To in-

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[3] PTI Environmental Services, 15375 SE 30th Place, Suite 250, Bellevue WA 98007.

crease the comparability of date gathered from Puget Sound, the Puget Sound Estuary Program (PSEP) Management and Technical Advisory Committees proposed the development of a set of standardized guidelines for all environmental investigators working in the Sound. The PSEP is one of the estuary programs in EPA's National Estuary Program, and both the Puget Sound and National programs are described in U.S. EPA, 1990.

The process for identifying which environmental variables needed specific standardized guidelines included obtaining answers to a series of questions:

1. Did more than one group measure the variable?
2. Were different methods used by the various groups to measure the variable?
3. Did the differences among the various methods limit data comparability among studies?
4. Did the inability to compare data among different studies limit the usefulness of that kind of information?

Once the need for standardized guidelines in Puget Sound had been established, it was essential to incorporate into their development realistic expectations as to their level of detail, flexibility and costs of implementation.

The guidelines do not cover the scientific design elements of an environmental sampling project, such as choice of variables and type, and number and timing of samples. They also do not address the statistical analysis, presentation or interpretation of sample data.

The guidelines have been designed to serve as guidance documents for carrying out environmental sampling and any subsequent laboratory analysis. The guidelines are generally written for a technically expert audience, and the nontechnical program manager is likely to have to consult with technical staff on application of a guideline. The program manager will have to decide whether the Puget Sound Protocols and Guidelines are appropriate for the particular objective the manager has in mind.

General Protocol Format

The presentation format for each of the fourteen subject areas is similar in order to facilitate their use. The following are the usual subject area sections and their order of presentation:

Use and Limitations — describes what the key variables measure and major limitations to the uses of the variables.

Field Procedures — describes container type, special cleaning procedures, collection techniques, sample quantity, preservation technique, storage conditions and maximum holding time.

Table 1.
RECOMMENDED PROTOCOLS AND GUIDELINES FOR MEASURING SELECTED ENVIRONMENTAL VARIABLES IN PUGET SOUND

Guidelines Title	Edition	*DOP
1. General QA/QC Considerations for Collecting Environmental Samples in Puget Sound	1st	Mar 86
2. Recommended Protocols for Measuring Conventional Sediment Variables in Puget Sound	1st	Mar 86
3. Recommended Guidelines for Conducting Laboratory Bioassays on Puget Sound Sediments	1st 2nd	May 86 Mar 91
4. Recommended Protocols for Station Positioning in Puget Sound	1st	Aug 86
5. Recommended Protocols for Measuring Metals in Puget Sound Water, Sediment and Tissue Samples	1st 2nd	Aug 86 Dec 89
6. Recommended Protocols for Microbiological Studies in Puget Sound	1st	Nov 86
7. Recommended Guidelines for Measuring Organic Compounds in Puget Sound Sediments and Tissue Samples	1st 2nd	Dec 86 Dec 89
8. Recommended Protocols for Sampling and Analyzing Subtidal Benthic Macroinvertebrate Assemblages in Puget Sound	1st	Jan 87
9. Recommended Protocols for Fish Pathology Studies in Puget Sound	1st	Jul 87
10. Recommended Protocols for Measuring Conventional Water Quality Variables and Metals in Fresh Waters	1st	Dec 89
11. Recommended Guidelines for Sampling Soft-Bottom Demersal Fishes by Beach Seine and Trawl in Puget Sound	1st	Jul 90
12. Recommended Guidelines for Measuring Conventional Marine Water Column Variables in Puget Sound	1st	Mar 91
13. Recommended Guidelines for Marine Mammal Tissue Sampling and Analysis	1st	Mar 91
14. Estuarine Wetland Restoration Monitoring	1st	Jan 90

** DOP = Date of Publication.*

Laboratory Procedures — describes analytical procedures (or provides the pertinent citations), laboratory equipment, sources of error and QA/QC specifications

Data Reporting Requirements — describes the kinds of data that the analytical laboratory should report and the units in which the data should be reported.

JUBILATIONS

The Puget Sound Protocols and Guidelines Document

As of January 1991, the list of Puget Sound Protocols and Guidelines includes fourteen subject titles covering some 1,000 pages of text (Table 1). Of these fourteen subject areas, two are in final stages of development (mammal tissue sampling and marine water column variables) and one is close to completion in a second edition (sediment bioassays).

Document Acceptance and Distribution

The current distribution of the Puget Sound Protocols and Guidelines is shown in Table 2. Fully 35 percent of the requests for the documents have been from outside the state of Washington, indicating an interest in the document at a national level. There are no comparative documents in use by the other EPA National Estuary Programs or by the Chesapeake Bay and Great Lakes programs. Each of these programs has had and will continue to have difficulty trying to use information gathered and analyzed by various means to determine conditions and trends in natural resources and water quality-related variables.

ISSUES

Adoption of the Puget Sound Protocols and Guidelines

Element L-3 of the Draft 1991 Puget Sound Water Quality Management Plan states that "The Authority, in consultation with EPA and Ecology, shall develop and implement a process for .... formal adoption of the protocols and guidelines" (Puget Sound Water Quality Authority, 1990, p.260). The protocols and guidelines are specified for all activities in the Puget Sound Ambient Monitoring Program. It was hoped that they would be further adopted by the majority of Puget Sound institutions with environmental investigation responsibilities. Staff at the three co-managing agencies for the Puget Sound Estuary Program (Washington Department of Ecology, Puget Sound Water Quality Authority and the U.S. Environmental Protection Agency) developed a process for the adoption of the PSP&G which consists of several steps:

Table 2.
DISTRIBUTION OF PROTOCOLS AND GUIDELINES

Location	Number of Copies	% of Total
Overseas	11	2
Canada	18	4
East Coast States	70	15
Southern States	13	3
Mid-West and Mountain States	9	2
West Coast States	40	9
Washington State/Puget Sound	306	65
Totals	467	100
Washington State/Puget Sound	306	65
Outside the state	161	35

1) Adoption of the PSP&G by the Puget Sound Water Quality Authority and the Puget Sound Estuary Program Management Committee.
2) Agreement within a regulatory or resource management institution, based on staff discussion and consensus, to adopt a policy of PSP&G use by its personnel.
3) Adoption of PSP&G use by agencies and organizations in the Puget Sound Basin through letters of agreement written by the appropriate policy-level managers to the Co-Chairs of the Puget Sound Estuary Program Management Committee.

The adoption process was started in early 1990. Concerns have been raised by regulatory program managers within some state agencies about the meaning of the word "adoption" and the extent to which the PSP&G then supersede other protocol documents. Where managers are in disagreement with sections of the document, they have been concerned that "adoption" will mean that they will be required by the agency to follow the PSP&G. The developers of the PSP&G have always kept in mind that there may be reasons why the Protocols and Guidelines might be considered inappropriate for a project, such as:

- The PSP&G do not address a particular environmental variable of interest;
- New research strongly suggests that the PSP&G recommendations are obsolete;
- The manager needs to follow other specified protocols or guidelines as a participant in a national data collection program;
- The manager is legally bound to follow methods inconsistent with the PSP&G;
- The manager cannot meet project needs by using the PSP&G, e.g., to do unscheduled/emergency sampling or a broad reconnaissance survey.

If use of the PSP&G is deemed inappropriate for any specific application, whether an agency has or has not adopted them, the project managers are requested to include an explanation in the project's quality assurance section addressing the reasons for deviating from the recommendations of the PSP&G, and the consequences for general data use as a result of the deviation. The PSEP Management Committee reserves the right to flag any such data in the Puget Sound Central Data Base as being inconsistent with the PSP&G. It is then left to any user of the data to decide whether the inconsistency is important enough to exclude this data from his or her analysis.

Long-term Funding for Maintenance

Substantial funding and effort have gone into preparing the PSP&G document. It is becoming a standard reference for Puget Sound. But it is going to require resources to maintain the document so that it remains useful. The PSEP Program envisions potential revision of all chapters on a three-year basis, but with the possibility of having more frequent revisions for those chapters where major changes can occur quite quickly, e.g., chemistry and bioassays. It would be tragic at this point if the document was to die on the vine because of lack of funding. Minimum annual maintenance support is most probably in the $50,000 to $150,000 range. The PSWQA has agreed in the 1991 Plan to take ultimate responsibility for the PSP&G, but this does not guarantee that sufficient funding will be forthcoming.

Maintaining the Integrity of the Document, or What's in a Name

The original title of the protocols document, Puget Sound Protocols, has caused two unanticipated problems, The reference to Puget Sound immediately provoked the question "Can or should these protocols be used elsewhere?" Some state and federal agencies would like to use these protocols in areas far from Puget Sound and would like to have the title changed accordingly. The PSEP has advised these agencies not to simply copy these protocols and re-issue them with a different title. The PSEP is concerned that if others merely republish the document under a different title, this could lead eventually to the development of several "versions" of these protocols by various agencies.

The second problem with the document's original title was the word "protocols". The PSEP didn't anticipate what this word connoted to certain scientists, especially chemists. The chemists felt that a "protocol" needed to be much more specific and detailed than the guidance given in the protocols document. In addressing this objection, the document name was changed to the Puget Sound Protocols and Guidelines.

Updates

Complete revisions to a subject area within the PSP&G might at best occur every third year. For some subject areas such as organic chemistry, inorganic chemistry and sediment bioassays, where changes to methods or new methods can occur frequently, the concern is that the PSP&G may quickly become obsolete. The plan has been to deal with this concern by sending out updates or changes to the document when a group of experts has agreed that it is time to do so.

Meeting Needs of Principal Users

There are times when the needs of an agency may run into conflict with the PSP&G. For example, sediment holding times for sediment bioassays have been much debated. The PSP&G recommends that the maximum holding time be two weeks, while the Puget Sound Dredged Disposal Analysis (PSDDA) program needs to authorize a maximum holding time of up to six weeks for programmatic reasons. While definitive comparisons of toxicity of sediments held for two weeks versus six weeks have not been conducted, all bioassays conducted with sediments held longer than two weeks are flagged as not meeting the requirements of the PSP&G.

The developers of the PSP&G kept in mind that specification of state-of-the-art methods could be unrealistic because of the costs involved and because the level of accuracy obtained with those methods might be unnecessary for many investigators. The goal has been to balance the sophistication and accuracy of methods with budgets, capabilities, and data uses. If state-of-the-art methods could be incorporated into such a balance, they would be preferred for use as standardized protocols or guidelines. Incorporation of future advances in methodologies could be achieved through revisions on a three-year cycle and, in urgent cases, by sending out copies of new or amended procedures to all document subscribers.

LESSONS LEARNED

While the PSEP continues to deal with a shrinking number of unanticipated issues connected with the PSP&G, some of the guidance given by Armstrong and Becker (1988) can be re-emphasized or expanded. Specifically, those planning to embark on a protocols and guidelines development process should:

- Involve as many entities that collect, analyze or use environmental information as possible in the protocols and guidelines development process;
- Encourage a skilled facilitator to actively draw out dissenting opinions at the workshops for each group of variables (These comments are much

easier to deal with at the workshop than later, when open discussions with numerous participants are either difficult or impossible to arrange.);

- Reference existing published protocols and methods as much as possible (*i.e.*, when they are easily obtainable from the published literature), rather than reproducing them in the protocols and guidelines document;
- Be aware that the adoption process is important to insure that state and federal agencies are aware of the use of the protocols and guidelines document whenever possible (However, this process is not trivial and may take a considerable amount of time and effort.); and
- Be aware of the need for funding to maintain, distribute and revise the document in the future.

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MONITORING OF HABITAT RESTORATION AND SEDIMENT REMEDIATION IN THE ST. PAUL WATERWAY

Don E. Weitkamp, Ronald L. Shimek, and George T. Williams[1]

INTRODUCTION

This paper describes biological and chemical monitoring results of the habitat restoration and sediment remediation conducted at the Simpson Tacoma Kraft Mill on St. Paul Waterway in Commencement Bay. Sediments adjacent to the Kraft Mill had been contaminated over many years by discharge of chemical contaminants and release of organic debris from log rafting, debarking, and wood chip handling. These actions had resulted in the contamination of about 17 acres of subtidal bottom by varying concentrations of chemical contaminants and organic debris.

The general area of contamination prior to the remedial actions was divided into three areas (Figure 1). Area A sediments had very high levels of chemical contamination plus considerable organic debris (30-70% total volatile solids). Area B had lower levels of chemical contaminants but considerable organic debris. Area C sediments had low levels of chemical contaminants but were covered by a layer of wood chips that provided a poor substrate for benthic organisms. Each area was covered by clean sediments from the Puyallup River as apart of the remedial action.

Remedial actions included source control, relocation-redesign of the outfall, and sediment remediation by capping. Source control actions removed contaminants from raw materials and eliminated stormwater runoff. Outfall design and relocation eliminated concentration of any materials carried by the effluent through much greater initial dilution and trapping in surface waters that move offshore. Capping of contaminated sediments isolated the contaminants from the Commencement Bay environment and provided an opportunity to construct new intertidal habitat.

The Simpson Tacoma Kraft Mill together with Champion International (former owners) worked with the Washington Departments of Ecology and Natural Resources to permit and construct the remediation in 1987. With the help of the Puyallup Tribe and other city, state and federal agencies, the project was approved in December 1987 and construction completed in August 1988.

[1] Parametrix, Inc., 3020 Northup Way, Bellevue, WA 98005

METHODS

Monitoring has been conducted for two years following completion of the new habitat and sediment cap. Monitoring methods were specified in the Consent Decree (State of Washington Department of Ecology v. Simpson Tacoma Kraft Company and State of Washington Department of Natural Resources. 1987), that formed the basic agreement for implementation of this remedial action.

Several different types of monitoring have determined the effectiveness of the new habitat and sediment cap. These include 1) physical monitoring, 2) chemical monitoring, 3) benthic monitoring, 4) epibenthic monitoring, and 5) monitoring of aquatic macrophytes. The following briefly describes the methods employed in each monitoring activity.

Physical monitoring has included both monitoring of elevations at specific points along established transects and general site contour mapping. Five transects were established perpendicular to the shoreline in the intertidal zone between +8 ft and -2 ft MLLW. During the first winter (1987-1988) these transects were monitored monthly. We again monitored once each year in 1989 and 1990. Provisions are included in the monitoring plans for a survey of the transects following any severe northerly storm. However, no such storm has occurred since completion of the new habitat. During June, extreme low tides of the entire new habitat and intertidal portions of the cap are surveyed each year to map elevation contours. All elevations are taken by theodolite and electronic distance measuring equipment.

Chemical monitoring has been conducted to determine if contaminants have been migrating through the cap at unacceptable concentrations. Some chemical migration was anticipated in the original design. Borings have been made through the cap annually at five locations. Samples have been collected at 1 ft intervals from elevations 1-2 ft and 2-3 ft above the cap-original sediment boundary, and from 2-3 ft below the top of the cap.

Surveys for benthic infauna have sampled surface sediments at four stations on the new habitat and cap, and at two reference stations. At each station five replicate 0.1m^2 van Veen grab samples were collected for preservation and sieving through a 1 mm screen following the Puget Sound Estuary Program Protocols (Tetra Tech, 1987).

Epibenthos samples were collected from six intertidal stations on the new habitat and two reference stations on the Puyallup River Delta. These included equal numbers at the +2 ft and -2 ft MLLW elevations. Samples were collected two times between May and June using a 0.018m^2 suction device with approximately 2 ft of water over each sample location.

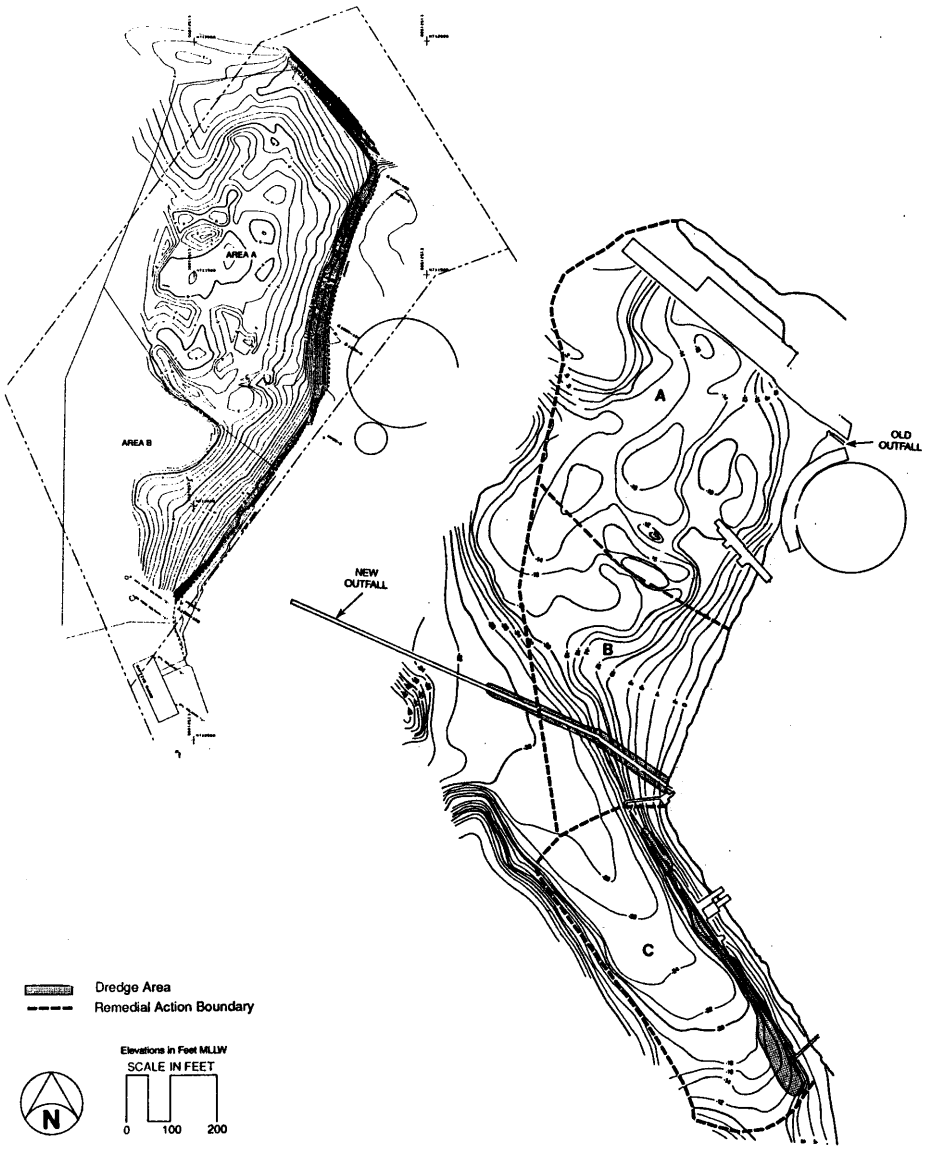

Figure 1.
ST. PAUL WATERWAY SEDIMENT SITE. *Constructed new habitat-cap above, original contours below.*

Aquatic macrophytes were assessed by ground surveys conducted during low tides of June and August. Aerial photographs taken in June were used to help map the distribution of vegetation. In 1990, ten line transects were established across the upper intertidal zone along which algal coverage was measured.

MONITORING RESULTS

Physical monitoring of the new habitat and cap has shown some redistribution of the intertidal portions as anticipated by the original design (Parametrix, Inc., 1990). In general, the elevations at the upper intertidal levels have shown mixed changes over the two years. The first transect at the northeastern edge of the new habitat has shown increases of 0.9-1.9 ft in elevations at most stations. This appears to be due to transport and deposition of Puyallup River delta sediments as was anticipated. The other four transects have shown mixed increases and decreases in elevations that are characteristic of sediment redistribution by wave action. These changes have ranged from decreases as great as 2.3 ft to increases as great as +3.5 ft. These changes have occurred in areas where the cap and new habitat are 8-20 ft thick.

Chemical monitoring has concentrated on those chemicals that were identified at high concentrations in the original sediments. By concentrating attention in the area just above the cap-original sediment boundary (1-2 ft and 2-3 ft), the chemical monitoring is serving as an early warning system. The criteria against which concentrations are measured are the 80% of the Lowest Apparent Effects Thresholds (AET) in effect at the time the consent decree was issued.

The samples closest to the sediment-cap boundary show the same low concentrations (generally below detection limits) as most other cap samples. Through 1990 these concentrations remained far below the 80% of lowest AET criteria. A few samples from one station near the northeastern edge of the new habitat have shown higher contaminant concentrations than other samples. We interpret these higher concentrations as evidence that small quantities of the original sediments were mixed with the first layer of the cap during construction, rather than contaminant migration. This interpretation is based on the sporadic occurrence of the higher concentrations and the presence of low concentrations at elevations below some higher concentration samples.

As anticipated, the new habitat was quickly populated with a variety of new organisms. Animals such as barnacles, shore crabs, and amphipods were present on portions of the new substrate before construction was complete. Monitoring of the benthic community in 1989 and 1990 indicates that the site is developing a community of organisms commonly found in shallow water on and in unconsolidated sediments. However, the constructed habitat is still new and undergoing colonization and population equilibration.

The benthic community has shown increasing complexity with time. In 1989 each station had about 50 taxa, with about 100 total taxa for the site. By 1990 the population had increased to about 80-100 taxa per station and 190 taxa for the entire site. These changes are primarily the result of many new taxa that are present only in small number; however, even the dominant taxa have tended to change. Such changes indicate the new community continues to develop and has not yet reached a stable stage.

Such changes are likely to be due to both interactions of the organisms and changes in the substrate. Some organisms, such as juvenile ghost shrimp (*Callianassa californiensis*), that were abundant in 1989 were adults by 1990 and thus were too deep in the substrate to be collected by the van Veen grab. Thus the data indicate a change when little real change in this species occurred. On the other hand, the surface substrate has changed at some locations to include a higher portion of fine-grain sediment. This physical change is apparently responsible for some of the changes in taxa.

The benthic community contains organisms characteristic of both clean and organically rich substrates. The small clam *Axinopsida serricata* is a dominant species that is characteristic of pollution free substrates (Armstrong, Thom and Chew, 1980). A dominant polychaete worm, *Tharyx multifilis* (Word et al., 1984), is characteristically found in both organically polluted and transition areas, while a dominant ostracode, *Euphilomedes* sp., is characteristic of transition zones near organically polluted areas. This mixture of dominant species in the new habitat appears to indicate that these are opportunistic species taking advantage of a new unpopulated substrate. Opportunistic species such as *Tharyx* and *Euphilomedes* have life-history characteristics that assist in their ability to rapidly colonize disturbed habitats (Zajac and Whitlatch, 1982 a and b).

By 1989 a substantial epibenthic community inhabited the new habitat. This community was highly variable between stations. In general the lower intertidal stations (-2 ft MLLW) had a higher abundance than higher intertidal stations (+2 ft MLLW). Abundance at each station tended to vary considerably between May and June but not in a uniform direction. Similar trends occurred in 1990. Epibenthos abundance at the new habitat stations tended to be in the same range as at the reference stations, with the exception of one extremely high reference sample in 1989.

The epibenthic populations include substantial numbers of known salmonid prey species (Simenstad et al., 1985). In general the prey species comprised 10-80% of all epibenthos found at the -2 ft elevation, but less than 10% of the epibenthos at the +2 ft elevation.

Macroalgae have established several communities on the new habitat. Although they have reached a stable state, they do cover a substantial portion of the new habitat. Most of the large rocks scattered throughout the intertidal area are covered with *Ulva lactuca, Enteromorpha* sp., *Fucus distichus* or *Bangia fuscopurperea.* These species cover little more than 50% of the rocks and larger gravel. Kelp (*Costaria costata* and *Laminaria* sp.) are commonly attached to rocks in the lower intertidal portions of the new habitat. The sandy portions of the new habitat provide a poor substrate for the species present, as shown by the 2-3% coverage of this substrate.

CONCLUSIONS

Monitoring has shown that the new habitat and cap are meeting the original objectives of the remediation project. The contaminated sediments are remaining isolated from the marine environment. The new habitat has become populated with substantial communities of benthos, epibenthos and macroalgae. The new habitat and cap are remaining in place with distribution of the surface sediment. Long-term monitoring will show if these trends continue.

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THE ARCO ANCHORAGE OIL SPILL — AN EVALUATION OF AVIAN IMPACT ASSESSMENT METHODS

Steven M. Speich[1], *Terence R. Wahl*[2], *and Robert U. Steelquist*[3]

INTRODUCTION

Responding to the ARCO ANCHORAGE Port Angeles oil spill of December 1985 presented several opportunities to implement and evaluate methods and procedures for assessing impacts to marine avian communities especially. Three elements potentially useful in this process are evaluated relative to the ARCO ANCHORAGE oil spill. In addition, the period since the 1985 spill has allowed us to develop several ideas concerning oil spill response, particularly avian impact assessment. This evaluation and discussion is intended to focus attention on the needs of avian impact assessment.

BASELINE INFORMATION OF NORTHERN PUGET SOUND WATERBIRDS

The only set of data with widespread coverage of northern Puget Sound marine habitats and marine bird populations available derived from NOAA's Marine Ecosystem Analysis (MESA), Puget Sound Project conducted in 1978 and 1979 (Manuwal et al., 1979; Wahl et al., 1981). Similar data for southern Puget Sound, the waters south of Admiralty Inlet, Hood Canal, and the waters east of Whidbey Island are limited (Wahl and Speich, 1983, 1984; unpubl. obs.). The numbers of breeding marine birds and the locations of their colonies also have been summarized through 1982 (Speich and Wahl, 1989).

Four major elements were generated as a result of the MESA surveys in 1978 and 1979, three of which are especially pertinent to the effects of the ARCO ANCHORAGE oil spill on marine birds. They are: 1) the seasonal occurrence and abundance of marine birds in distinct marine habitat areas; 2) the bird habitat/oil index; and 3) the rate of occurrence of dead birds on selected beaches. These are evaluated below. The fourth element, the numbers of breeding marine birds and their colony locations, is not considered here, as the spill did not occur during the period in which colonies are active, thus not allowing us to relate exposed birds to specific colonies in Puget Sound.

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Characterization of Marine Bird Populations

The major set of data to emerge from the 1978 and 1979 MESA marine bird censusing program was seasonal abundance and distributional information on all waterbird species in 72 marine habitat areas (subregions) in northern Puget Sound (Manuwal et al., 1979; Wahl et al., 1981). The MESA program was, and remains, the largest and most extensive censusing program ever carried out in the inland marine waters of Washington. There were over 7,100 censuses during the study, using a variety of techniques and observation platforms (aircraft, lengths of beaches, boats, ferries, and points along shorelines). However, even with this effort the results are best described as a characterization of the seasonal abundance and distribution of waterbirds.

That such a description of the data set is accurate is evident when specific attempts are made to utilize the information. A logical question to ask following an oil spill that affected waterbirds is how many of each species numbers were lost. One way to determine that is to census the population after the event, and compare the pre- and post-spill totals (means). In the case of the Port Angeles ARCO ANCHORAGE spill, there were many censuses in the Port Angeles harbor and adjacent areas during the 1978-1979 study. Thus it needs to be determined what type of censusing effort would be needed to statistically demonstrate losses.

The comparison of means from before and after a spill is one approach to detect changes in numbers, providing that statistical requirements are met. We wanted to determine the number of replications of censuses needed to detect a given true difference between two means (Sokal and Rohlf, 1981). To evaluate this we selected the Port Angeles harbor data set, generated by 26 separate censuses during the winter periods of 1978 and 1979. Eight species present on all censuses were chosen; however, departure from the expected normal distribution was significant for three species and they were not considered. The species with the lowest percent coefficient of variation (45 percent), the bufflehead (*Bucephala albeola*), was selected first. To detect, at the .05 level of significance, a 5 percent change in numbers present, 80 percent of the time, would require over 1,200 censuses both prior to and after an event, clearly an impractical task. To detect a 20 percent change in numbers would require about 80 censuses, and to detect a 50 percent change would require about 15 censuses, before and after the event.

The above example illustrates the difficulties in establishing a baseline of information adequate for post event comparison to detect event-related changes. It is clear that with the above approach it is only reasonable to detect relatively large changes in numbers, and that a modest portion of the time. However, other sampling and statistical approaches that may be more practical to conduct and more sensitive to changes need investigation. It is also

necessary to determine how important it is to detect changes of a given proportion. Clearly an "immediate" assessment of impacts from a single event, perhaps catastrophic, is desirable, and the techniques are likely to be different than those for detecting the effects of small but chronic pollution events over longer periods of time, such as years. Perhaps it is only necessary to detect large changes in numbers; even if small changes could be detected, it may never be certain that they were not the result of other processes affecting the system.

The placement of census transects, the choice of areas sampled, is critical to evaluate oil spill impacts on waterbirds. This is clearly illustrated in the Port Angeles ARCO ANCHORAGE spill by the fact that the number of red-necked grebes (*Podiceps grisegena*) recovered (unpubl. obs.) far exceeded the number projected to be in the area from the 1978-1979 baseline (unpubl. data). During the baseline study, Port Angeles harbor was censused often and thoroughly throughout the year, and few red-necked grebes were encountered. To the east (extending to Pt. Wilson), the shoreline and close-in nearshore waters were censused from aircraft, a small number of shore stations, and on a few occasions by small boat. Another census transect extended from the tip of Ediz Hook at Port Angeles to the midpoint of Dungeness Spit, well off shore. An examination of the path of the oil slick during the first night, especially, and of the original census routes revealed that the red-necked grebes were largely in an area outside of the nearshore transect, and inside of the outer transect. The transects did not sample the marine habitat zone—in this case a relatively broad, shallow area occupied by the red-necked grebes. Most other northern Puget Sound marine habitat areas were more representatively sampled during the MESA program.

Another factor that could prove important in limiting the usefulness of any baseline data set is changes in the numbers of individuals of species present in Puget Sound habitats from year-to-year as well as changes over longer periods of time. Fluctuations in numbers of a species present in Puget Sound habitats from year-to-year are expected, and may reflect either changes in numbers of birds using Puget Sound or other alternative areas or actual changes in the species' populations. Even if small changes in numbers could be practically detected, it could be difficult to separate changes due to an oil spill from those resulting from natural processes. Comparisons to control areas, areas not directly affected by the spill being considered, may help to interpret any changes detected. In any case, whether small or large changes are being examined, reference to one or more control areas is likely to be both desirable and necessary.

The Bird/Habitat Oil Index

An objective of the 1978 and 1979 MESA censusing program was to characterize the seasonal abundances and distribution of waterbird species in marine

habitat areas of northern Puget Sound (Manuwal et al., 1979; Wahl et al., 1981). However, it was most important in meeting MESA objectives to use abundance data in such a manner as to reflect both the importance of areas to waterbirds and the relative vulnerability of the avian community present to oil, should it appear in a marine habitat area. To accomplish this we developed a relatively simple bird oil index (BOI) that quantifies various aspects of species' behavior (biology, distribution and abundance) as they relate to potential exposure to oil on the water surface (see Speich et al., 1991 for detailed description). We used the BOI system to evaluate the relative importance of oil pollution to waterbirds in different marine habitat areas of Puget Sound (Wahl et al., 1981).

When the BOI system was applied to the marine waterbird data obtained during the 1978 and 1979 censusing program, Port Angeles harbor and areas to the east and west received low to moderate rankings in all seasons (spring, summer, fall and winter), whereas other areas farther away received higher rankings. For example, the nearshore waters off Jamestown received the highest ranking in three seasons and a high ranking for the fall period. The open waters of the Strait of Juan de Fuca received the highest ranking in the fall period, reflecting the influx and passage of large numbers of common murres (*Uria aalge*) from colonies on the Oregon coast. In total, 72 subregions in northern Puget Sound received seasonal rankings. Generally, the marine bird populations occupying marine habitat areas in and near Port Angeles were not of exceptional or high importance/vulnerability relative to all of northern Puget Sound and the potential effects of oil pollution (see Wahl et al., 1981 and unpubl. data for details and species exceptions).

Based on the rankings given to marine habitat subregions, it is tempting to use the information to predict the impact of an oil spill on waterbird populations in a given area or in several areas. It is also tempting to compare the impacts of a spill to prior determined rankings. Likewise, it is possible to compare individual species' BOI values, or to use them alone. We feel all of these are improper uses of the BOI system. Rather, the BOI system is designed to help managers and others make decisions based on entire communities; it is not a predictive tool (Speich et al., 1991). Thus, the BOI system, although useful in making informed management decisions, is not useful in evaluating the impacts on waterbirds as a result of the Port Angeles ARCO ANCHORAGE oil spill, or to predict the impacts of future oil spills. It does identify locations where impacts from oil spills can be expected to be worst.

Rates of Occurrence of Dead Birds

The 1978 and 1979 MESA program also resulted in the determination of the rates of occurrence (birds/km) of dead waterbirds on 28 selected stretches of beach in northern Puget Sound (Wahl et al., 1981; Speich and Wahl, 1986). Included were six beach segments on Dungeness Spit (three on the outside

facing the Strait of Juan de Fuca and three on the inside facing the inner harbor and bay). The baseline data from the Dungeness Spit surveys were especially useful in assessing impacts to avian populations from the ARCO ANCHORAGE oil spill.

On 22 December 1985, the day following the evening of the oil spill, it became apparent that relatively large numbers of oiled birds were coming ashore on the beaches of Dungeness Spit. Over the next few days oiled birds were recovered from the beaches of Dungeness Spit and to a lesser degree from other beaches in the area (Steelquist, unpubl. data). In total over 1,900 waterbirds impaired by the oil spill were recovered.

The rates at which oiled birds were recovered from Dungeness Spit beaches were dramatically greater than the rates observed in 1978 (0.21 birds/km) and 1979 (0.28 birds/km) (Figure 1). Post spill recovery rates were 29.75 birds/km on 22 December, 17.3 birds/km on 23 December, 12.65 birds/km on 24 December, and 42.09 birds/km for the three days combined. In relative terms, the rates were many times greater than comparable rates for 1978 and 1979 (Figure 2): 138 and 170 times baseline on 22 December, 82 to 62 times on 23 December, 60 to 45 times on 24 December. For the three days combined the rates were 200 and 150 times greater than the 1978 and 1979 survey rates. It should be noted that these are minimal rates derived from only the first three days of a recovery period that lasted several more days. Moreover, the three day sample period in 1985 was shorter than the sample period of the baseline study.

Though post-spill shore, boat and aerial censuses provided much evidence of changes in bird distribution and abundance, as well as antidotal observations of excessive preening behavior, low sampling frequency (see above) precluded *statistically* demonstrating changes. Unfortunately, therefore, the recovery of oiled live and dead birds was the only direct, quantitative evidence of the effects of the oil spill on waterbird populations. In this case the baseline was sufficient, when compared to post-spill rates, to demonstrate impacts convincingly. This was largely possible because Dungeness Spit is an exceptional depositional area where currents catch and transport incapacitated birds to the beaches (Ebbesmeyer et al., 1979, 1991). In addition, most of the oiled birds were recovered alive and it is reasonable that oiled live birds swam to shore after currents transported them near Dungeness Spit.

Although recovered oiled birds are tangible evidence of spill impacts, their total numbers are a minimal estimation of the numbers impaired. Relating numbers found dead or impaired to numbers actually oiled is imprecise due to the uncertainty associated with oiled birds appearing on beaches, and their eventually recovery (see Page et al., 1990; Speich et al., 1991; and Speich and Thompson, 1987).

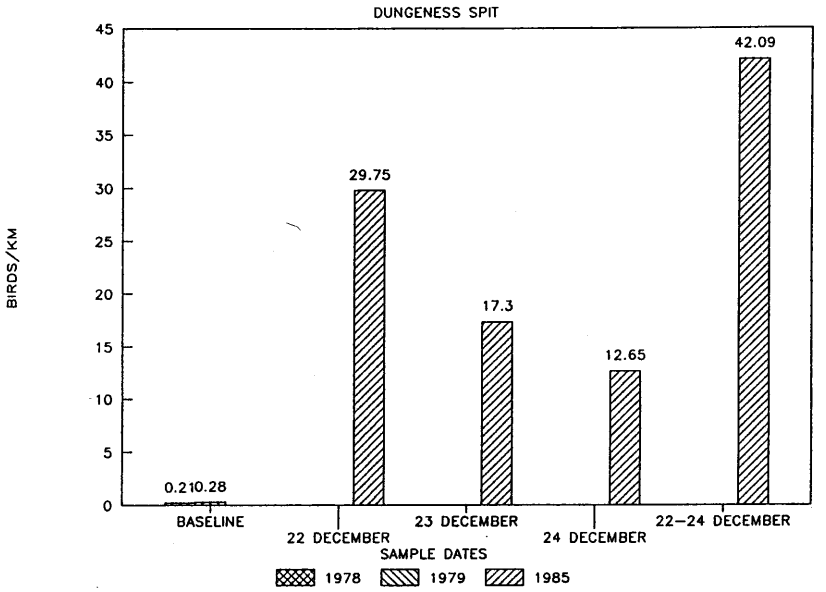

Figure 1.
***RECOVERY RATES (BIRDS/KM) OF OIL IMPAIRED BIRDS** from Dungeness Spit beach transects, 1978 and 1979 (baseline) and 22 through 24 December 1985.*

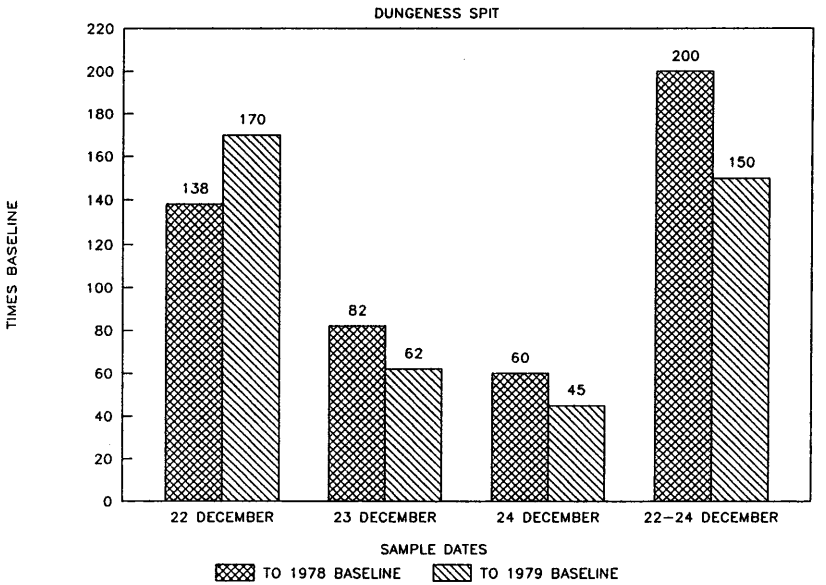

Figure 2.
***COMPARISON OF RECOVERY RATES OF OIL IMPAIRED BIRDS,** 22 through 24 December 1985, to 1978 and 1979 baseline rates from Dungeness Spit beach transects.*

THOUGHTS RELATIVE TO SPILL RESPONSES

Primarily based on our experiences from the ARCO ANCHORAGE Port Angeles oil spill, several thoughts that we feel are important and useful in determining impacts to avian populations from future oil spills are discussed. There is clearly much work yet to be done.

Establishing Monitoring Areas

A number of representative marine habitat areas should have ongoing monitoring programs. However, *first*, the specific uses and goals of the program must be clearly identified. The monitoring program should use MESA program or other compatible methods, all data should be entered into a continuously updated and user-available data base, and the program should be developed with careful attention to experimental design and the requirements of statistical analysis.

At least two factors should be considered in selecting habitat areas for monitoring. First, censuses should be located in areas of known seasonal concentrations of waterbirds, areas we know contain sizeable populations. Areas selected should also include at least representative seabird colony sites. Monitoring site selection should be based on likelihood of spills occurring there, or that winds and currents likely would carry spilled oil into sites. Candidate areas should include those with known exposure from terminals, anchorages, refineries or transport lanes.

Based on the above factors, several northern Puget Sound areas are probable candidate sites: Rosario Strait, Strait of Juan de Fuca, Cherry Point, Fidaglo, Bellingham and Padilla bays, Guemes and Bellingham channels, Port Angeles area, and the south shore of the San Juan Islands. Areas not impacted can serve as control sites.

Assessing Spill Impacts

There are at least three general processes for determining the impacts of oil spills on marine bird populations. It is important that a process be selected, developed, and put in place ahead of time, for *immediate* and *unhindered* implementation, in the event of a spill. A combination of processes may be appropriate.

These processes are: (1) develop a statistically sound experimental design that incorporates reliable and practical methodology to allow for the detection of changes in seabird populations; (2) develop an attitude which accepts systematically taken, well documented data, and expert, experienced opinion as indicative of real changes due to impacts, even though sampling effort may not be statistically sufficient; or (3) develop a formula based on calculated

subregion vulnerability of birds and other organisms that accesses monetary damages without further reference to censuses of populations.

Two information needs arise from oil spill impacts. One is related to the frequent requirement that the spiller be assessed a monetary fine for impacts to marine ecosystems, often based on a demonstration of impacts to organisms—thus the need for acceptable processes. However, satisfying the requirements for impact assessment, based on demonstrated impacts or a predetermined formula, does not eliminate the need for scientific studies of impacted communities.

Volunteer Data Collection

Experience from the ARCO ANCHORAGE oil spill illustrate pitfalls and opportunities in establishing and using baseline data. As shown above, baseline data is useful when combined with rate of occurrence of dead birds.

Certain problems occur, however. Rates of occurrence of dead birds on Dungeness Spit were recorded only with the assistance of a large number of well organized volunteers whose primary task was the recovery of live, impaired birds for transport to a rehabilitation center. Such volunteer assistance, while predictably based on the high interest and motivation of the volunteers following major oil spills, is not generally organized and managed to yield relevant data. Typically, spill response managers are not prepared to organize volunteers for data gathering purposes. In the case of the ARCO ANCHORAGE, the seabird recovery was specifically designed to collect data on occurrence rates to match the 1978 and 1979 MESA beach transects. Volunteer teams were assigned to carefully delineated beach sectors, used standardized reporting methods, and were debriefed after their beach walks.

Following major oil spills, the major emphasis of volunteer effort is on the live recovery and rehabilitation of impaired birds. Although wildlife managers often argue that these activities have negligible affects on seabird populations, it is clear from the ARCO ANCHORAGE experience that occurrence data provided as a byproduct of the seabird recovery were of significance.

We urge that this benefit be considered in future discussions regarding both the use of volunteers in wildlife recovery and usefulness of recovery itself. Furthermore, specific measures should be taken to ensure that, in the unfortunate event that another oil spill affects Dungeness Spit, recovery teams are trained and utilized to collect data on rate of occurrence of both live and dead birds that will compliment both the MESA and ARCO ANCHORAGE data sets.

As a corollary, we urge that when baseline data bases are designed and established consideration be given to the mobilization of volunteers for ongoing monitoring or spill related biological data collection.

ACKNOWLEDGMENTS

This paper benefitted from our conversations with H.R. Carter and R.G. Ford.

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LONG-TERM TRENDS IN PUGET SOUND MARINE FISHES: AN EXAMINATION OF SELECTED DATA SETS

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INTRODUCTION

The primary objective of this project was to analyze for long-term trends in Puget Sound marine fish distribution and abundance based on a synthesis of available data. A secondary objective was to establish a baseline against which future fish monitoring efforts can be compared and evaluated.

A goal of the Puget Sound Estuary Program is to characterize the study region through a system-wide synthesis and analysis of existing data on water and sediment quality and living resources, in order to identify spatial and temporal changes in the estuarine system and to evaluate probable causes for these changes. A recent evaluation of historical data sets on Puget Sound marine fishes (Moulton and Miller, 1987) reviewed information on location, date, gear used, number of sets made, depths sampled and types of data recorded to determine if these data were available in sufficient temporal and spatial coverage, and of sufficient quality, to evaluate trends in selected fish species at selected locations. The conclusion was that the data existed at some sites to examine trends over long periods of time.

MATERIALS AND METHODS

Utilized Data Sets

Geographical distribution data—Presence or absence data was examined for selected species of fish as reported in the primary literature, technical reports, log books and miscellaneous sources from the mid-1800s to the early 1970s (over 200 data sources; see Miller and Borton, 1980). Fish species were selected for analysis if they fell into one of two categories: (1) rare species of marine fishes that entered Puget Sound from ocean waters on occasion or historically had rarely been observed, and (2) marine fish species that were commonly caught in research trawls in Puget Sound.

University of Washington beach seine data — A series of similar beach seine collections were made at the Golden Gardens (Seattle) beach between 1950 and 1967, with some periodic sampling after that. These data were transferred from the original logbooks to data entry forms, and then entered into the computer for analysis.

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University of Washington research trawl data—These data were considered excellent for the objectives of this project because they were collected primarily under the direction of three researchers using standardized data collection techniques. In the preliminary survey of available data, areas that showed the greatest potential for evaluating trends were Port Orchard, Port Gardner, Bellingham Bay, Port Madison and Case Inlet. Since the most promising data sets appeared to be from Port Gardner, and due to the general difficulty encountered in formatting the data from all locations, only trawl data from Port Gardner were analyzed for this project.

Analysis Methods

When evaluating historical data that was originally collected without the objective of long-term trend analysis, it is necessary to do a "retrospective analysis" which relies on the reconstructions of long term records from existing data (Champ et al., 1987). With this approach, the analysis techniques are dictated by the quality and quantity of the long term data. Both qualitative and quantitative analyses of long term data are useful because the emphasis of such studies is on trends. Causality, however, cannot be determined, although some correlations may be observed.

Rare species presence or absence, 1863-1987—This analysis was conducted on the geographical distribution data and only included rare species records that had been verified by an expert. Fish distribution records archived at the University of Washington until 1976 were examined for the occurrence of 27 species deemed to be rare. These records were compared to similar lists of 11 rare species from 1863 to 1987 maintained by Dr. Alan Mearns at NOAA, and of 5 rare species from 1977 to 1987 recorded by Washington Department of Fisheries.

Common demersal species frequency of occurrence—The analysis was also conducted on the geographical distribution data, but in this case only frequency-of-occurrence of Puget Sound demersal fishes was considered. The analysis only considered fishes caught in demersal nets, since this was the largest data set, and focused on common demersal species to reduce error associated with recording and species identification.

In order to standardize for effort, we divided the number of occurrences of each species in each year by the number of occurrences of English sole (*Parophrys vetulus*) in the same year. English sole is the most ubiquitous, abundant, and commonly identified species likely to occur in a trawl; thus it was considered that the number of English sole reports would approximate the number of trawls made in a given year. These "English sole" catch-per-unit-effort (CPUE) values were used to analyze for trends in common demersal species. The English sole frequency of occurrence reports showed a general increase from the 1930s into the late 1960s. Since then, the occurrences have decreased, but with considerable variability.

Central Puget Sound species diversity and abundance — This analysis utilized data from the Golden Gardens beach seine (1950-1972) and Port Gardner Bay trawl (1965-1987) data sets. Species diversity and species richness as described by Pielou (1975) were evaluated through time. At Golden Gardens, changes in abundance of English sole were evaluated, while at Port Gardner Bay the abundance of 14 species was analyzed.

RESULTS

Rare Species Presence or Absence, 1863-1987

The data indicate that peak occurrences of rare or uncommon species appear to have occurred during the early 1870s, the early 1880s, 1918, the mid-1960s, 1972, and 1983.

Common Demersal Species Frequency of Occurrence, 1932-1972

Research trawl data on species that have commercial or recreational value indicate little change in the relative abundance of dogfish (*Squalus acanthias*) from the late 1940s through the early 1970s. Pacific cod (*Gadus macrocephalus*) increased from the 1940s to mid-1970s, when CPUE peaked, then declined until 1980, when CPUE appears to have stabilized. Shiner perch (*Cymatogaster aggregata*) showed an increase in CPUE from the 1940s to the early 1970s, although a noticeable drop occurred in the late 1960s (Figure 1a). Other shallow water flatfish, overlapping in many habitats with English sole, starry flounder (*Platichthys stellatus*) and rock sole (*Lepidopsetta bilineata*) (Figure 1b) also showed a general increase in abundance in the 1960s. Sand sole (*Psettichthys melanostictus*) showed little change. Flathead sole (*Hippoglossoides elassodon*) and Dover sole (*Microstomus pacificus*) (Figure 1c), which generally overlap with English sole only in deeper water, both seemed to show decreases in relative abundance from the 1930s to the early 1970s.

Long-term data were available for five species of fish that are not considered to be commercially or recreationally important, and which presumably have populations little influenced by fishing: ratfish (*Hydrolagus colliei*), tomcod (*Microgadus proximus*), staghorn sculpin (*Leptocottus armatus*), roughback sculpin (*Chitonotus pugetensis*) and snake prickleback (*Lumpenus sagitta*). All of these species, except ratfish, showed a period of peak relative abundance in the early to mid 1960s, similar to the pattern of shiner perch (Figure 1a). In general, ratfish showed a declining trend in the early 1950s, then stabilized (Figure 1d).

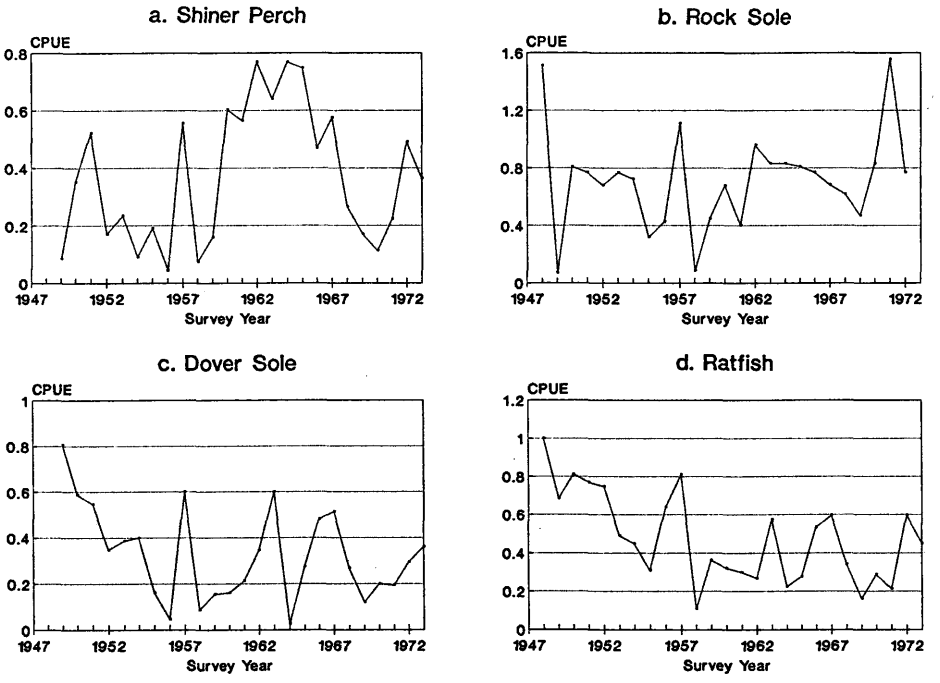

Figure 1.
YEARLY CPUE OF SHINER PERCH, ROCK SOLE, DOVER SOLE AND RATFISH FROM RESEARCH SAMPLING IN PUGET SOUND, 1947-1973 *(CPUE = number of occurrences/number of occurrences of English sole).*

Central Puget Sound Species Diversity and Abundance

Golden Gardens demersal fishes — A plot of the number of species caught during the spring at Golden Gardens from 1950 to 1972 revealed a significant decline ($p<0.05$) in the number of species, from 40-50 in the early 1950s to 15-20 in the early 1970s (Figure 2a). A species diversity index also indicated a similar decline, although the relationship was not statistically significant. The catch rate of English sole did not change significantly during this period.

Port Gardner demersal fishes — The number of species present and species diversity of the 14 most commonly caught species did not show any trends or statistically significant differences from 1965 to 1986.

Six species, English sole, starry flounder, sand sole, rock sole, slender sole and staghorn sculpin, had sufficient data to examine trends in CPUE. Of these six species, English sole (Figure 2b), starry flounder and sand sole showed statistically significant declines ($p<0.05$) in CPUE. The rock sole, slender sole and staghorn sculpin data were extremely variable and did not show any trend in CPUE over time.

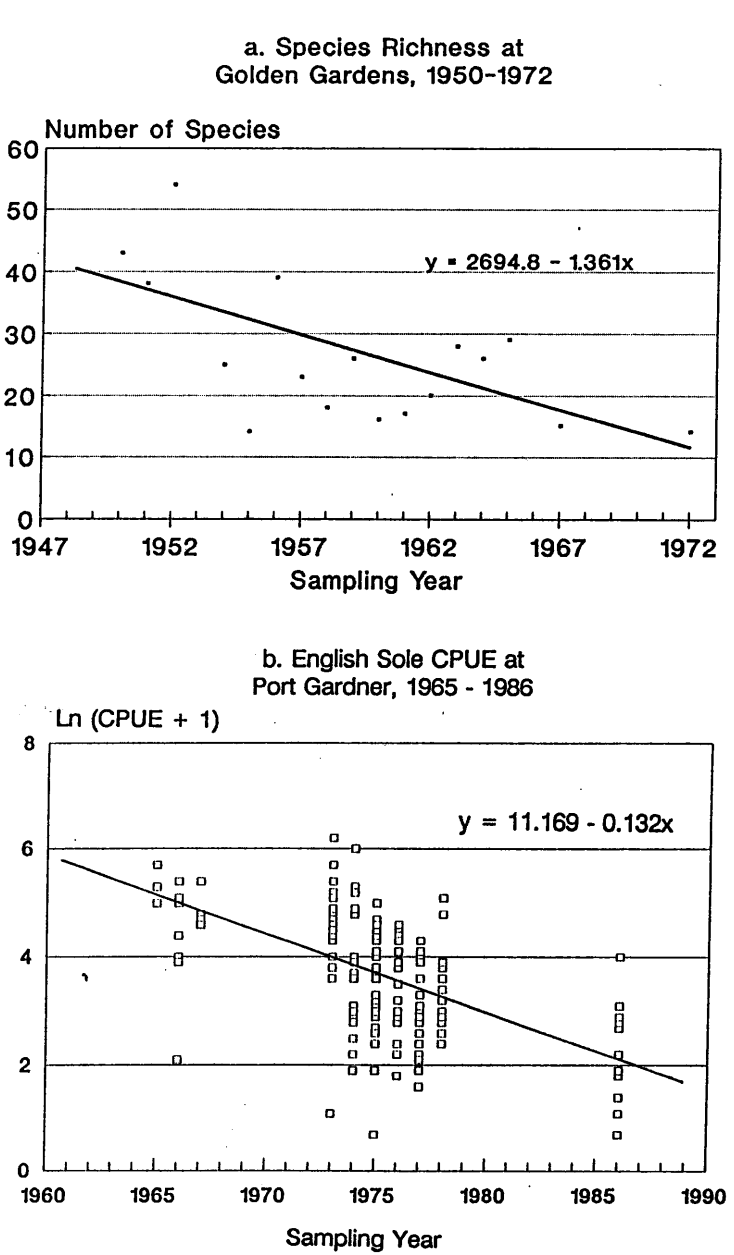

Figure 2.
TRENDS OF SPECIES RICHNESS AT GOLDEN GARDENS (1950-1972) AND ENGLISH SOLE ABUNDANCE AT PORT GARDNER (1965-1986).

DISCUSSION

Rare Species Presence or Absence, 1863-1987

The occurrence of rare species can provide a rapid indication of changes in the marine environment. Ebbesmeyer et al. (1988) have documented temperature changes in the Puget Sound area from 1916 to 1987, and there do appear to be reasonably good correlations of peak rare species occurrences and unusually cold (1918-1919, 1971-1975) or warm (1963-1965, 1983-1984) years, except for 1932-1935 which were transition years from warm to cold temperatures. We feel that maintaining records of unusual occurrences of rare or exotic fishes can provide an early warning of changes to Puget Sound.

Common Demersal Species Frequency of Occurrence, 1932-1972

There was a period of increased catch rates for several common shallow water species (i.e. shiner perch, roughback sculpin, staghorn sculpin, tomcod, sand sole, and snake prickleback) during the early to late 1960s. After this time period, the catch rates generally returned to pre-1960 levels. Other species did not show similar periods of increased abundance, and some deep water species, such as Dover sole, flathead sole, and ratfish, appeared to show decreases.

It is interesting to speculate that the years of peak abundance (1960-1968) of several species might be correlated with warm water years of approximately the same time period, especially when recognizing the unlikeliness of a direct correlation due to the life history patterns associated with the species. Unfortunately, the compilation of research data from other warm water years is inadequate or simply has not yet been completed.

Central Puget Sound Species Diversity and Abundance

The data from Golden Gardens from 1950 to 1972 indicate a significant decrease in the number of species. While the data support such a trend, the analysis is strongly influenced by high values during the first three years of sampling (1950-1952). After that period, the number of species appears reasonably stable. However, the number of species never exceeded 30 after the construction of the Shilshole Breakwater in 1959.

At Port Gardner, measurements of species diversity and richness were stable from 1965 to 1987, but catch rates of three species decreased. The reason for the decrease in English sole, starry flounder and sand sole catch rates is not known, but certainly Port Gardner is an urban environment that has undergone continual alteration.

Utility of Examined Data as Baseline For Future Monitoring

We think that monitoring of rare/unusual fishes is useful baseline data and can be done relatively easily and accurately, and should be done formally, instead of informally as is now the case. Conversely, recording the frequency-of-occurrence of reports for common species and standardizing the data to English sole was useful in generally detecting major changes, but the method is too qualitative for monitoring purposes.

We think the use of standardized trawl and beach seine catches for long-term trends in CPUE data, such as analyzed in this report at Golden Gardens and Port Gardner, is the approach to use in monitoring the long-term health of Puget Sound marine fishes. Assuming that monitoring of marine fishes will be part of the EPA Puget Sound Ambient Monitoring Plan which will follow EPA protocols, the compilation and analysis of other data sets should be completed where past sampling was conducted in the same manner as recommended in the standardized protocol. These data need to be compiled into a useable data base to ensure that they do not become lost or unusable as researchers come and go over the years.

New data that are collected in a standardized fashion should be added to the data base at regular intervals to ensure that (1) the data base remains current, and (2) data do not become lost through lack of proper documentation.

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USE OF CHRISTMAS BIRD COUNT DATA FOR MONITORING MARINE BIRD POPULATIONS

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INTRODUCTION

Many species of marine birds and waterfowl are residents of the Puget Sound basin. An even greater number use the Sound seasonally as a resting and foraging site along the Pacific Flyway migration route. Both resident and migratory bird populations are vulnerable to destruction of habitat critical to rearing, feeding, and refuge, overfishing of food supplies, and bioaccumulation of contaminants in the ecosystem, as well as to the more direct human impacts from oil spills, gill netting, hunting, and lead poisoning from ingestion of used shot.

As human development and industrialization in the Puget Sound basin increase, the pressures on these species become greater as limited habitat declines in size and quality. Adequate population estimates needed for effective management require population surveys of both summer breeding ground and winter distribution (Cummins et al., 1990; Kraege, 1990). Regular surveys are conducted on breeding populations of only a few species. Even then, without supplemental information on the nonbreeding populations, species status may not be known.

Marine birds are regularly surveyed at principal breeding islands, but there have been few comprehensive surveys to estimate abundances (Wahl et al., 1981; Wahl and Speich, 1983 and 1984). Species with more widespread breeding sites are even less well understood. Waterfowl have received relatively more attention since they have been managed for hunting, although it is still impossible to distinguish the effects of environmental factors from those of habitat loss or hunting mortality.

Without adequate funding in the foreseeable future for collecting the large amounts of needed information, it becomes important to accumulate any supplemental data that can provide more insight into these species' population status and trends. Research has helped to understand the breeding biology of a few species such as the rhinoceros auklet (Richardson, 1961; Leschner, 1976; Wilson and Manuwal, 1986), although much remains to be learned. Other less traditional sources of information are available, but each must be viewed in light of its inherent limitations if useful insight is to be gleaned.

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In this study, we investigated the use of the Christmas Bird Count (CBC) as a source of data to monitor long-term trends in marine birds and waterfowl. CBC sites in Puget Sound encompass important breeding and foraging habitat for many species of marine birds and waterfowl that reside in or migrate through Puget Sound. We compared CBC data with other data sets collected by state and federal agencies to determine the best methods for analyzing the CBC data and whether CBC data could provide population trend information, and to identify the limitations of the data set.

METHODS

The Christmas Bird Count is conducted each December by Audubon Society volunteers who count all species observed in one day in designated 15-mile diameter sites across North America. In 1988, parties of observers, each with a trained leader, spent a combined 1800 hours covering 14 Puget Sound sites. Most of this effort is conducted on land or along shorelines, although some observations are conducted by boat. The data is summarized onto standard reporting forms, checked for completeness and errors, and sent to Cornell University for compilation.

Christmas Bird Count data for the winters 1960-61 through 1987-88 were collected from the Christmas Bird Count database at Cornell Laboratory of Ornithology. The data for 1963 through 1972 in the CBC database has been truncated after two digits. For example, a count of 119 birds was recorded as 110. Comparison with actual numbers recorded for the rest of the data could cause a bias of up to 10 percent, but the average expected is one percent and is not considered a significant source of error (G.S. Butcher, pers. comm.).

Fourteen locations that had continuous records for part of the period were included in the analyses (Figure 1). One site which had only one year of data in 1964 was not included. There were only three locations before 1974, but new sites have been added regularly to reach the current 14-site coverage in 1988. Some sites have moved, but for the purposes of this study are considered the same since the new locations had over 50 percent overlap with the old locations.

For each site we extracted the species count and observer party-hours (total hours at a site observer parties spent counting birds) for each species of marine bird and waterfowl. An index was calculated by dividing the species count by the party hours and multiplying by one hundred (number/party-hrs X 100). This index has been proven as a valid method to standardize the count to observer effort in previous CBC studies (Bock and Root, 1981; Buchanan, 1988).

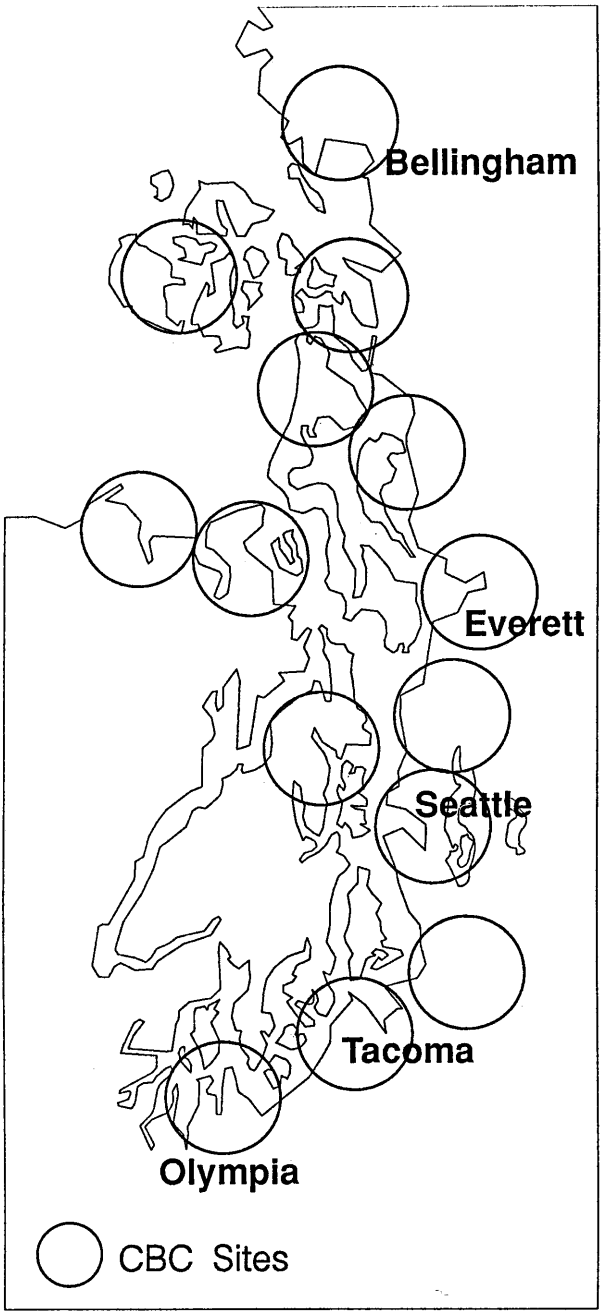

Figure 1.
CHRISTMAS BIRD COUNT LOCATIONS IN PUGET SOUND.

It has been suggested that no standardization is required, since any marine birds visible will be counted regardless of effort. However, since additional sites are added over time, the standardization to observer effort was used to help correct for the changes in geographical coverage.

Standardized data were summed over the 14 sites for individual species and some waterfowl species groupings. Additionally, waterfowl species groupings were also summed over specific sites or site groups that covered important winter foraging habitat. These results were compared with the analysis for all sites to determine the best grouping for monitoring. All sites were included in the analysis for marine birds because winter distributions of many of these species are poorly understood. Results were compared with available survey data on several species.

Waterfowl results were compared with results from yearly midwinter aerial surveys conducted by the Washington Department of Wildlife (WDW) and the U.S. Fish and Wildlife Service (USFWS) (Kraege, 1990). Marine bird species counts are more dependent on visibility, a factor which can limit the effective coverage of marine waters by land or boat observers. This results in highly variable coverage of marine habitat from the one day CBC counts. Therefore, marine bird sums were averaged over three year periods to partially account for such highly variable counts and coverage. This method has been used by Raynor (1975) and Bock and Root (1981). These results were compared with data collected on marine bird breeding surveys (Wilson, 1977; Manuwal et al., 1979; Wahl et al., 1981; Galusha et al., 1987; Speich and Wahl 1989; U.W. Wilson, pers. comm.). The WDW surveys were not used for comparison, since they focus on waterfowl and count marine birds only incidentally.

RESULTS

CBC locations were added over the years, thereby increasing the geographic coverage in Puget Sound from over 700 square miles in 1974 to over 2400 square miles in 1988. CBC data for several species with different habitat requirements and winter distributions were analyzed to determine what effect the addition of short-term records have on the count index trends. Removal of locations with fewer years of observations, while changing the index values, did not affect the observed trends in any case tested. Therefore, all locations regardless of length of record were included in the results.

Waterfowl

The WDW compiles seasonal maximum counts for the snow goose (*Chen caerulescens*) population that winters in the Skagit River delta region from the WDW midwinter inventory data. Figure 2 compares the WDW abundances with the five CBC locations that cover the Skagit area and the snow goose

habitat fairly well. With the exception of an anomalistically high CBC count in 1982, the CBC index appears to closely follow the trends of the WDW survey results.

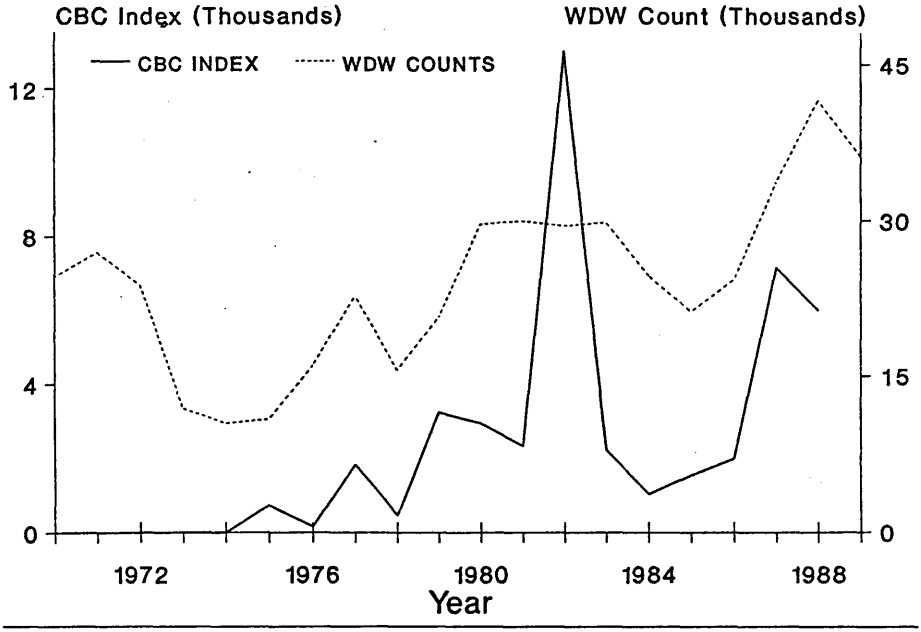

Figure 2.
COMPARISON OF SNOW GOOSE COUNTS IN THE SKAGIT DELTA AREA.

The WDW midwinter inventory also tracks abundances for diving duck species that winter in Puget Sound (Table 1). Duck species are more dispersed throughout the Sound than are snow geese. Therefore, CBC counts for all locations were summed and indexed to compare with the WDW inventory results (Figure 3).

CBC counts project a pattern that appears to lag one year behind the WDW survey trends. We cannot explain this result which may be an artifact of the data. After 1980, when most of the 14 sites are included in the counts (improving geographical coverage), the CBC data do suggest the nonsignificant downward trend documented by the WDW inventory (Kraege, 1990). While varying from the WDW survey data more than the snow goose results, the CBC counts again exhibit the trends identified in the WDW data.

The CBC count data for dabbling duck species (Table 1) are compared to WDW midwinter inventory counts in Figure 4. The WDW data suggests no discernible trend and are characterized by large variability. The CBC data also suggest fairly constant results, although the variability is three times that for the

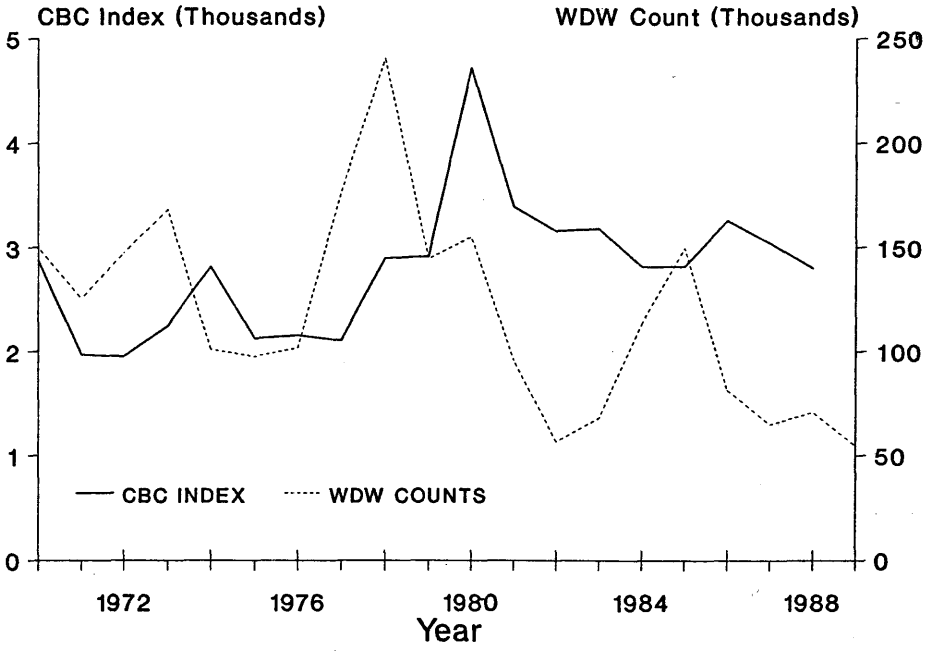

Figure 3.
COMPARISON OF DIVING DUCK COUNTS IN PUGET SOUND.

Table 1.
SPECIES OF DIVING AND DABBLING DUCKS WINTERING IN PUGET SOUND INCLUDED IN THE CHRISTMAS BIRD COUNT ANALYSES.

Diving Duck Species	Dabbling Duck Species
Surf Scoter *Melanitta perspicillata*	Mallard *Anas platyrhynchos*
Black Scoter *Melanitta nigra*	American Widgeon *Anas americana*
White-winged Scoter *Melanitta deglandi*	European Widgeon *Anas penelope*
Barrow's Goldeneye *Bucephala islandica*	Green-winged Teal *Anas flavirostris*
Common Goldeneye *Bucephala clangula*	Blue-winged Teal *Anas discors*
Bufflehead *Bucephala albeola*	Cinnamon Teal *Anas cyanoptera*
Greater Scaup *Aythya marila*	Northern Shoveler *Anas clypeata*
Lesser Scaup *Aythya affinis*	Pintail *Anas acuta*
Canvasback *Aythya valisineria*	Gadwall *Anas strepera*
Ring-necked Duck *Aythya collaris*	
Harlequin Duck *Histrionicus histrionicus*	
Common Merganser *Mergus merganser*	
Red-breasted Merganser *Mergus serrator*	
Hooded Merganser *Lophodytes cucullatus*	
Oldsquaw *Clangula hyemalis*	
Ruddy Duck *Oxyura jamaicensis*	

diving ducks. The CBC results again reflect the significant factors of the WDW results (level, although highly variable, population), although the year-to-year comparisons with the WDW data show much greater differences than for either the diving ducks or the snow goose data.

Marine Birds

Four species of marine birds that use Puget Sound in the winter were selected: great blue heron, pelagic cormorant, pigeon guillemot, and rhinoceros auklet.

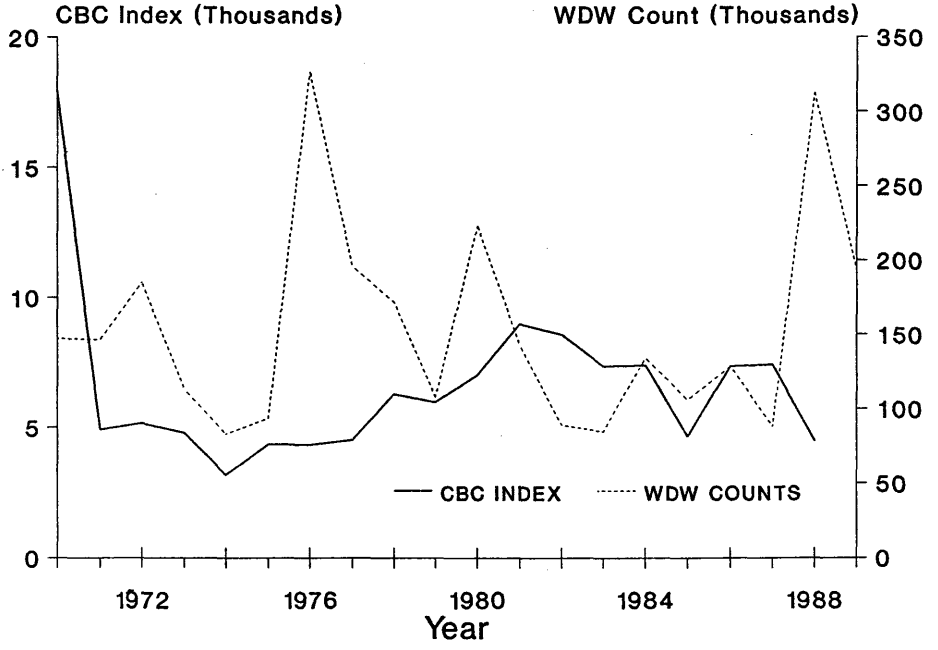

Figure 4.
COMPARISON OF DABBLING DUCK COUNTS IN PUGET SOUND.

All four species breed in Puget Sound but have varying nesting and foraging requirements. The three year averaged CBC count indexes for these four species are presented in Figure 5. Note that these records go back to 1961, although relatively few sites existed prior to 1974; the earlier data should be interpreted with greater caution. Comparisons of these trends to other existing time series data available for these species are discussed below.

DISCUSSION

Waterfowl

Comparison of the CBC results with those of the WDW midwinter inventory suggests that documented trends may be reflected in the CBC results. In the three waterfowl cases tested, the non-statistical correlation appears to improve with the more recent records. This should not be surprising, as the counts have become more consistent and better error checking of results has occurred in recent years. Also, as participation at each site increases, coverage of the site and the species present will improve. The best correlation is with the snow goose trends, where most of the species' preferred winter habitat is covered by CBC sites.

The importance of selecting appropriate sites for comparison is also apparent from the waterfowl results. The apparent correlation in the snow goose counts disappeared when all Puget Sound sites were included. That is to be expected, since the species is rarely found at other sites. By adding sites outside the range of the species, the increased effort with little if any additional sightings skews the CBC index and increase its error. Therefore, for species with fairly defined distributions, site grouping may have significant effects on the results. Also, if site coverage of the distribution is fairly complete, then no standardization to effort may better reflect true abundance.

For species distributed throughout the Sound, inclusion of all sites is preferred. Subsets of sites that focused on prime habitat areas of the north bays did not improve the correlations to the documented trends for dabbling ducks over the results when all sites were included. The CBC index appears to improve as an estimate of change in abundance if all areas of species normal occurrence are included, not just those areas of species concentrations. Conversely, lack of coverage of habitat should increase the error of the CBC index unless, by chance, the CBC sites reflect a stratified sampling scheme of a species' habitat preferences. They are certainly not selected as such. The CBC diving duck data may have reflected the WDW trends better if more portions of important wintering habitat along Hood Canal were included in the CBC counts.

Marine Birds

The CBC data can only provide estimates of relative changes in abundance for those species that winter in Puget Sound. Four species with different nesting and foraging habits were selected to assess the usefulness of the CBC index in assessing marine bird population trends. However, as addressed above, only a few other surveys to assess marine bird populations in the late 1970s and early 1980s were done with which the CBC results can be compared. While this

is not enough information to distinguish trends, the surveys have provided information on winter distributions (Wahl et al., 1981; Wahl and Speich, 1983) that can help to interpret the CBC results:

Great Blue Heron (*Ardea herodias*) — In winter great blue heron forage in tide flats, estuaries and nearshore waters throughout Puget Sound, usually close to their inland rookeries. This distribution and their large size insures good coverage of birds present at CBC sites. Figure 5 depicts an increase through the end of the 1970s, with the count leveling off and possibly showing a slight decline in the 1980s.

The initial increase is reflected in the heron nest counts from nesting surveys made over the same time frame (Calambokidis et al., 1985; Norman, 1988). However, the nest counts at surveyed sites continue to increase through 1988, while the CBC data suggest a leveling off. It is not known how the nest counts correspond to population size, and little data has been collected on nest use at

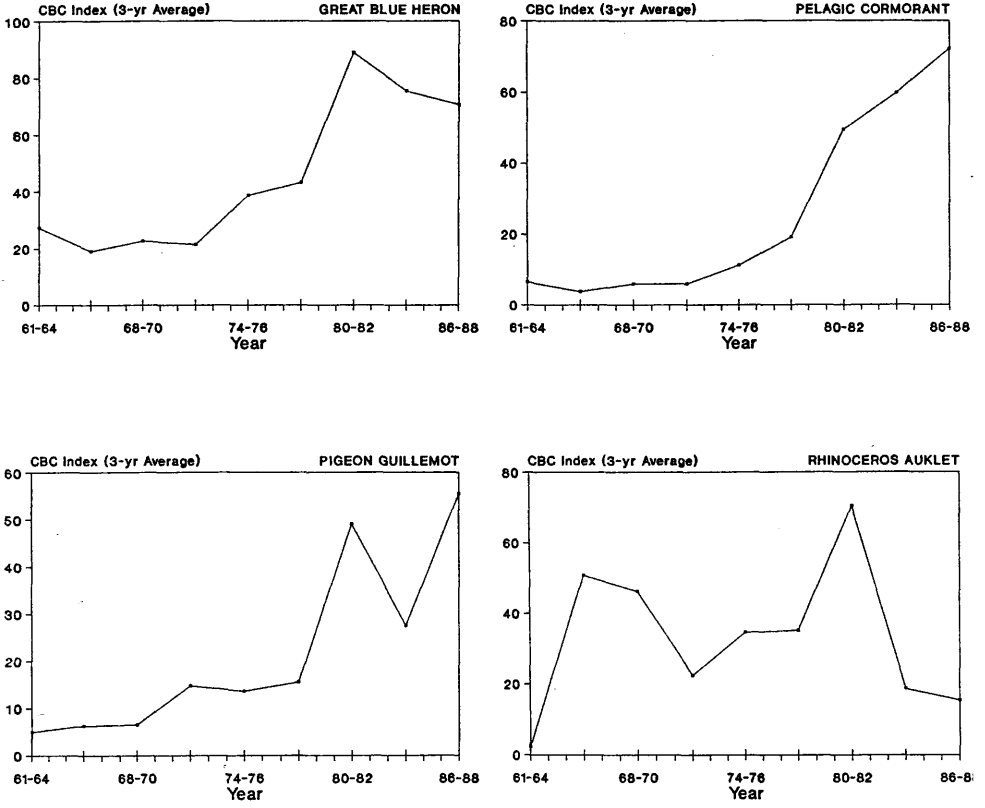

Figure 5.
CHRISTMAS BIRD COUNT INDEX RESULTS FOR FOUR MARINE BIRD SPECIES.

each site. It is also not known if the increase in the CBC index results from the discovery of new nesting sites within the CBC sites or from a true population increase. Further investigation of count reports and future counts could resolve these issues and identify whether the recent CBC index decline is reflected in the population.

Pelagic Cormorant (*Phalacrocorax pelagicus*) — Pelagic cormorants nest almost exclusively in the northern Sound on a small number of islands. However, during the winter they migrate throughout Puget Sound to forage in a variety of waters for a wide range of prey. Cormorants are usually easily seen perched to dry out between dives. This allows for fairly comprehensive counting, but species (the pelagic, and the larger Brant's and double-crested cormorants) can be confused at a distance. Figure 5 indicates a consistent, significant increase in the count index since the early 1970s.

This increase is reflected in the data collected at the main breeding site on Protection Island, where the colony has shown a consistent increase in breeding pairs since 1973 (Wilson, 1977; Galusha et al., 1987; Speich and Wahl, 1989; U.W. Wilson, pers. comm.). The Protection Island colony has historically accounted for the majority of the Sound's population.

Pigeon Guillemot (*Cepphus columba*) — The pigeon guillemot has a more widespread distribution than other alcids, with small groups breeding at sites in many of the remaining undisturbed bluffs and beaches throughout Puget Sound (Speich and Wahl, 1989). The majority of the population breeds in the north Sound islands, principally Protection Island, but individuals are widely dispersed in winter. These birds tend to stay in shallower waters along the shore and in kelp beds, preying mainly on small fish collected throughout the water column. Since guillemots stay out on the water throughout the winter, accurate counting is difficult. Figure 5 also depicts a significant increase in the CBC index for pigeon guillemots starting in the 1970s.

The increase is reflected in the breeding censuses on Protection Island (Galusha et al., 1987; Speich and Wahl, 1989; U.W. Wilson, pers. comm.) which show a consistent increase in breeding pairs from 1976 through 1984, with only a slight increase since then. The CBC results show much higher variability than those for the pelagic cormorant, possibly due to the stronger dependence on sea state and visibility for accurate counts of the individuals actually present.

Rhinoceros Auklet (*Cerorhinca monocerata*) — The Puget Sound population of rhinoceros auklets nest almost exclusively on Protection Island. Auklets feed primarily on bait fish in more open waters and channels. They also stay out on the water all winter. Although large numbers migrate to the Pacific, a portion stays in Puget Sound, usually in small to medium size groups. The CBC index for the rhinoceros auklet in Figure 5 indicates no discernible trend. The count results are highly variable but fairly consistent.

The lack of any long term change in the index is reflected in surveys. Breeding censuses from Protection Island indicate that the population may have leveled off, if not slightly declined, since 1975, although no figures were available after 1984 (Galusha et al., 1987; Speich and Wahl, 1989). The high variability in the CBC index may result from certain behavioral habits of the species. The flocking tendency of the auklet increases the patchy distribution of the bird, which can result in more variable counts. The deeper water habitat preference means that the birds are usually farther offshore, increasing the influence of visibility on the counts made from shore. Also, it is not known if the portion of the population that remains in the Sound is the same every year. Until more information is known about the winter distribution, the utility of the CBC index as an estimate of relative abundance of the rhinoceros auklet will remain debatable.

Other Uses of CBC Data

The results of this study also suggest that other species may be appropriate to investigate using CBC data. Shorebirds that winter in estuaries in Puget Sound may be useful to count at CBC sites that include suitable intertidal mudflat habitat. Dunlins (*Calidris alpina*), black-bellied plovers (*Pluvialis Squatarola*) and greater yellowlegs (*Tringa melanoleuca*) have been documented at south Sound sites (Buchanan, 1988). The Dungeness and Padilla Bay CBC sites cover habitat used by large wintering populations of Brants (*Branta bernicla*).

Results of the CBC index may also be useful in identifying the reasons behind documented population changes. By comparing feeding or habitat requirements between species, differences in trends may identify suspected causes for the change. For example, the decline of diving ducks compared to that of dabbling ducks may be related to feeding preferences or degradation of habitat. The diving ducks feed almost exclusively in marine waters on fish, while the dabbling ducks feed in fresh and salt waters, primarily on emergent vegetation and detritus.

CONCLUSIONS

The CBC can be considered a relative estimate of abundance useful in identifying trends for certain species of marine birds and waterfowl. However, interpretation of the results is only relevant when there is additional information concerning the species' winter distributions and behavioral habits available to understand the count's limitations. The CBC index trends reflected waterfowl species abundance estimates and four species of marine birds' breeding population estimates. Variability increased in the CBC index trends for species when counts were more dependent on visibility and when site coverage did not sample significant portions of prime habitat.

All surveys have limitations and biases and need to be interpreted with the effects of those limitations on the data in mind. The CBC is no different. The CBC is a one day count that, in most cases, covers only a portion of the habitat a species will utilize. One day sampling increases the results' dependence on the visibility, sea state, the completeness of site coverage by the observer party routes, and the distribution of flocking species. As in any census not conducted at breeding sites, diving species will be underestimated relative to surface feeders (Manuwal et al., 1979). Such limitations have to be considered when selecting species appropriate for CBC monitoring and when interpreting those results.

Further analyses should be conducted to identify if further refinement of the CBC index as a surrogate for estimates of abundance trends can be achieved. Party route information will need to be reviewed to gain further understanding of the count results. In particular, records may detail reasons for certain anomalous results, such as lack of coverage of previously counted areas and visibility problems.

Focus on developing new CBC sites in undersampled areas will also improve the CBC as an effective monitoring tool. Additional sites in Hood Canal would expand coverage in Puget Sound. At present, the CBC can provide good trend estimates of appropriate species with distributions in the north Sound embayments and down through south Sound. However, if Hood Canal is prime habitat for a species, then the information will be less accurate.

ACKNOWLEDGEMENTS

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GRAY WHALES IN PUGET SOUND AND THE STRAIT OF JUAN DE FUCA

John Calambokidis[1], Gretchen H. Steiger[1], Joseph R. Evenson[1], James C. Cubbage[1] and Richard W. Osborne[2]

INTRODUCTION

The range of the California gray whale (*Eschrichtius robustus*) extends from the calving lagoons in Baja California during the winter to major feeding areas in the Bering and Chukchi Seas (Rice and Wolman, 1971). Not all animals migrate to these northern areas. Summer sightings of gray whales have been reported in Mexico and California (Pattern and Samaras, 1977), Oregon (Sumich, 1984), Washington (Flaherty, 1983), and British Columbia (Darling, 1984).

We review the results of our research on gray whales that occur in the Strait of Juan de Fuca and Puget Sound. Much of this research has been opportunistic, but we also report the results of dedicated research conducted in the southwestern Strait of Juan de Fuca in 1986 (Calambokidis et al., 1987).

METHODS

Both dedicated and opportunistic vessel surveys were used to study gray whales from 1984 through 1990. Dedicated boat surveys were conducted every month from August 1985 to July 1986 and covered 1,825 nautical miles (nm) along shoreline areas (<3 nm offshore) in the southwestern Strait of Juan de Fuca, extending from Tatoosh Island east to Pillar Point. Additionally, opportunistic vessel surveys were conducted throughout Puget Sound as a part of other research projects and also in response to reports of gray whale sightings from the public. Surveys were generally conducted from Achilles inflatable boats with outboard motors.

Aerial surveys were flown in a Cessna 172, a single-engine high-wing aircraft. We flew 15 aerial surveys covering 1,135 nautical miles specifically to search for gray whales in the southwestern Strait of Juan de Fuca between August 1985 and July 1986. Additional aerial surveys were flown in other parts of Puget Sound as a part of other research efforts, especially in the summer and fall of 1984.

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[2] The Whale Museum, P.O. Box 945, Friday Harbor, WA 98250

Size classes of live whales were determined through aerial photogrammetry. Aerial survey aircraft were maneuvered directly over whales at altitudes of 400-600 feet. Vertical photographs were taken out the open window with a Nikon 35mm camera equipped with a 200mm lens. Scale was derived from calibrated focal length and barometric altimeter readings corrected with photographs of measured objects near the subject whale taken on the same day. Aerial measurements of a whale that was later found dead were 2.9% less than true ground measurements of the animal.

Photographs were taken of gray whales for photo-identification of individuals, primarily from boats. Both sides of an animal's back were photographed with a 35mm Nikon camera and 200mm or 300mm telephoto lens. Color print film (generally KR-400) was used through 1986, with black and white film (Ilford HP-5 pushed to 1200 ASA) used later. Individual whales were identified from prints by coloration, mottling, scars and barnacles. A photographic catalog of the different individuals was compiled and used as a reference to determine the identity of whales encountered later. In all cases where a close photograph was taken, the pictures allowed an unequivocal determination of the identity of the animal. Although whales were most often identified from photographs taken during boat surveys, some gray whales could be identified from photographs taken during aerial surveys.

Recent sightings of marine mammals were provided by the Whale Museum (Moclips Cetological Society) in Friday Harbor, Washington. The Whale Museum database contains over 10,000 marine mammal sightings in Washington State collected by researchers or the general public through the Whale Hotline since 1976. Additional information on sightings of gray whales were provided by the public and other researchers. Newspapers on several occasions requested people call to report sightings of gray whales.

Strandings of gray whales were recorded by participants of the Northwest Marine Mammal Stranding Network. Records of strandings were compiled by the National Marine Fisheries Service that coordinates this network.

RESULTS

Sighting Locations and Timing

Gray whales were reported in the Puget Sound region in all months of the year. Most sightings, however, were in spring and summer. Although there were inter-year variations, gray whales were seen for prolonged periods in multiple years in several regions (Figure 1).

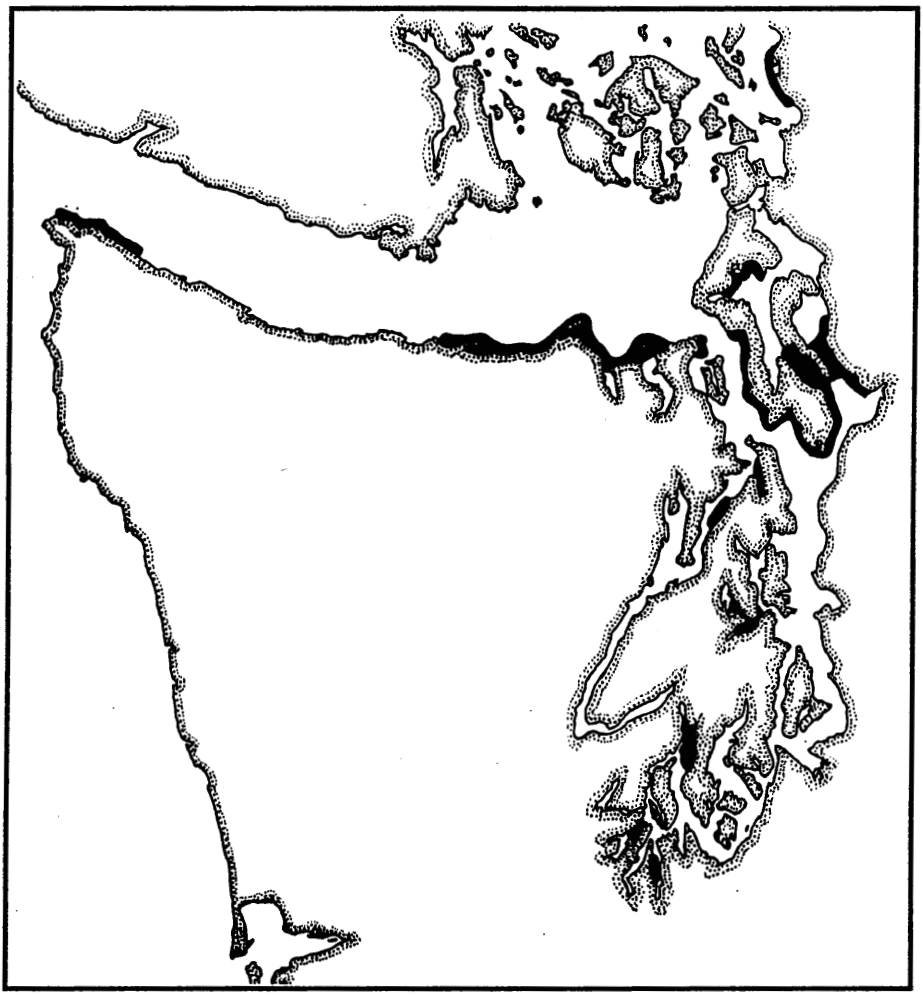

Figure 1.
REGIONS WHERE GRAY WHALES WERE OBSERVED FOR PROLONGED PERIODS IN MULTIPLE YEARS (SHADED). *Does not include British Columbia and Washington outer coast.*

Sightings of gray whales in different regions during the same time period provide a minimum estimate of the number of animals in the Puget Sound region. In early July 1984, aided by media requests, we received over 100 sighting reports of gray whales. Based on the number of whales reported, timing, and location of these reports, we concluded a minimum of 6-7 gray whales were present in the Puget Sound region at that time. Similarly, in April 1990, media coverage again helped prompt a large number of sighting reports.

Although these reports extended over a broader time period compared to 1984, we estimated 5-10 gray whales were in the Puget Sound region.

Individual Identification

Since 1984, we have identified 25 live gray whales in Puget Sound, the Strait of Juan de Fuca, and off the northern Washington coast. A total of 40 individuals have been identified if we include additional photographs provided by cooperating researchers off southern Vancouver Island.

Several animals were seen in different locations, including one inter-year resighting of an identified individual. An individual identified off the northern Washington coast (off Portage Head) by Cascadia researchers on 10 August 1989 was again photographed off southern Vancouver Island, British Columbia on 23 August 1990 (photograph from Pam Stacey and Robin Baird). Another gray whale photographed off Kayak Point in Port Susan on 3 May 1990 was photographed on 5 June 1990 near Victoria, Vancouver Island by Diane Claridge.

Within-year resightings of identified animals indicated whales remained in a particular area for extended periods. Five identified whales were photographed at the same location more than 2 months apart and an individual was seen multiple times over a 104 day period. Sites where the same individual was seen over a prolonged period (> 60 days) include along the southwestern coast of the Strait of Juan de Fuca (two animals), around Protection Island (one animal), and in southern Puget Sound (two animals). These residency times are minimums and based on identified individuals. Sighting reports of gray whales in a particular location often extended over a longer time period than our photo-identification effort.

Sightings and Movements in Southern Puget Sound in 1990

In 1990 we gathered extensive information on several gray whales that made prolonged stays in southern Puget Sound. The first sightings of a gray whale in Puget Sound in 1990 were on 12 March near Seattle, with the first sightings south of the Tacoma Narrows on 15 March. From 15 March through 2 June, Cascadia Research and the Whale Museum received 183 sighting reports of gray whales in southern Puget Sound (Figure 2). Sighting reports covered 57 days during this 79 day period, suggesting a continuous presence of animals.

Two gray whales showed a clear preference for four locations. Initially the whales were primarily seen in Henderson Bay near Purdy. Later one or both were commonly seen just outside Rocky Bay in Case Inlet, Totten Inlet, and near Olympia Shoal in Budd Inlet. At all four locations whales were observed milling and apparently foraging for prolonged periods in the same area.

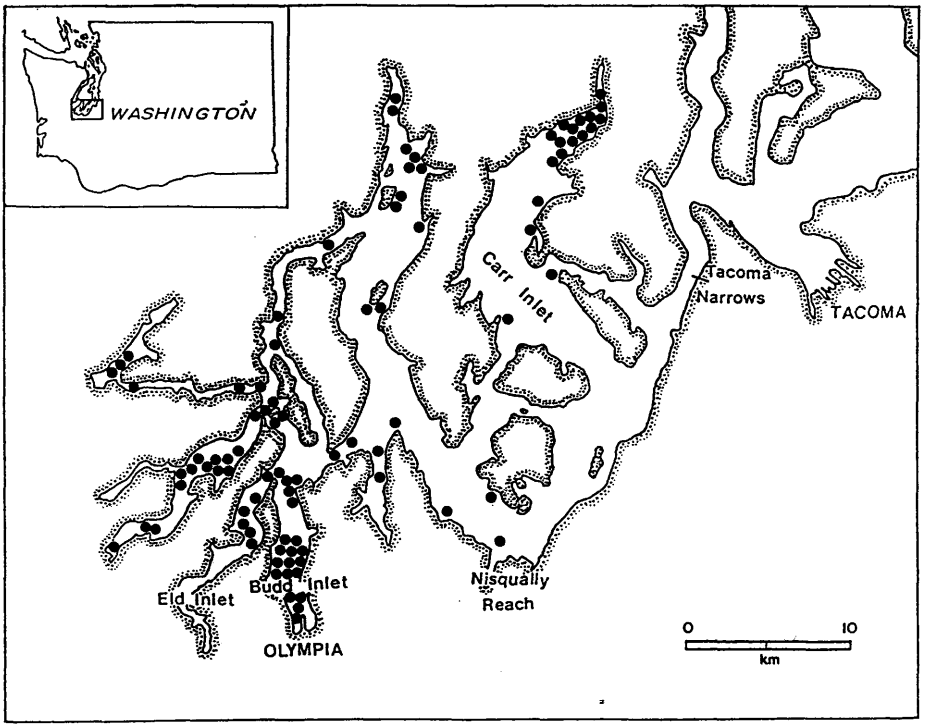

Figure 2.
LOCATIONS OF SIGHTINGS OF GRAY WHALES IN SOUTHERN PUGET SOUND BETWEEN MARCH AND JUNE 1990. *One dot represents one or more sightings in one location per day.*

These two gray whales attracted considerable publicity on 28 March when they entered a small tidal lagoon (Burley Lagoon) at the north end of Henderson Bay and became trapped. The whales were observed entering the lagoon at 0600 at high tide. The whales were trapped throughout the day by the shallow water at the entrance to the lagoon and were still trapped at 2200. They apparently left during the nighttime high tide, because both were outside the lagoon at first light the following morning.

Three different whales were identified in southern Puget Sound in 1990. Two whales, named Spot and Wanderer, were sighted most often and were identified at multiple locations, including Burley Lagoon, between 24 March and 30 May. Spot was identified photographically on 14 different days and Wanderer on 12 days. One other individual was identified on a single day, 12 April, in Budd Inlet.

Observations in the Southwestern Strait of Juan de Fuca in 1986

During surveys in the southwestern Strait if Juan de Fuca from August 1985 to July 1986, we made 68 sightings of gray whales (not including the sightings of migrating whales west of the Strait). Sighting frequency steadily increased from January through the end of observations in July.

Seven different animals were photographed and identified in the southwestern Strait of Juan de Fuca between January and July 1986. These seven animals accounted for 55 of the 68 gray whale sightings in this area. Of these seven animals, five were observed on multiple occasions in the study area. These five animals were seen from 3-28 times on 2-17 different days.

One individual appeared to remain in the study area during the period most gray whales make the winter migration south to Baja, Mexico. This whale was identified at the end of January and in February; however, reports of a gray whale in December and January in the same area may have been of the same individual.

Behavior

Gray whales were commonly observed foraging during our observations. In both Puget Sound and the Strait of Juan de Fuca animals seen from the air were obviously feeding; either mud was streaming from the whales' mouths or they were on their sides in kelp beds with their mouths open. We presumed that observations from land and boats of gray whales milling, going back and forth in the same area, indicated foraging.

Individual whales did not have exclusive feeding areas. Up to four different identified whales were seen foraging at different times at the same location in the southwestern Strait of Juan de Fuca. Similarly, three different whales foraged at different times within a two-week period in central Budd Inlet. Two identified gray whales in southern Puget Sound in 1990 were observed foraging together repeatedly at four different locations. These animals were often moving together within a few meters of each other.

Age-class of Live Animals in the Study Area

Lengths of nine live whales, measured by aerial photogrammetry between May and July in 1984 and 1986, ranged between 7.1 and 9.3 m. All but one animal were within the 7.0 to 8.6 m range expected for yearlings (Sumich, 1986; Heyning and Dahlheim, in press). The other animal was larger, but smaller than the 11.1 m size of sexually mature adults. Five of the nine whales measured were individually identified animals. Some of the other identified whales we tracked by boat appeared to be larger than these five; however, they were not measured with photogrammetry. Though our sample is small, it does

indicate that a high proportion of the gray whales that spend prolonged periods in the spring and summer in the Puget Sound region are young animals.

Mortality and Strandings

Between 1977 and 1990, 59 dead gray whales were examined by the Northwest Marine Mammal Stranding Network in Washington. Eighteen whales were female, 32 were male, and 9 were not determined. Total lengths were reported or estimated for 54 of these whales; using length/age analyses reported by Sumich (1986) and used by Heyning and Dahlheim (in press), we estimate that 4% were calves, 46% were yearlings, 20% were juveniles, and 30% were sexually mature.

Of these whales, ten died within Puget Sound proper (south of Admiralty Inlet). The highest number of whales that died in one year in this region was three in 1984. Lengths indicated that 6 of 10 were yearlings, two were juveniles, and two were sexually mature. Four were males, five were females, and the sex of one was undetermined. Of the six whales we tracked when alive in Puget Sound (using photo-identification), two were found dead later.

Sampling and determining cause of death of these whales is difficult due to rapid decomposition, lack of funding, and logistical complications. One yearling gray whale found dead in Makah Bay in 1986 had rope marks around its peduncle and flukes, leading us to conclude it had been entangled in a fishing net. We received a number of reports of gray whales caught in nets since 1981, including two caught in 1984.

DISCUSSION

Gray whales have been found to spend prolonged periods through the summer feeding along the west coast of Vancouver Island (Darling, 1984). These animals arrived as early as mid-April and remained to mid-September, when observations ceased. Through photo-identification, animals were found to return for up to eight years, although a majority (61%) of the animals are seen only in one year. Most of these animals appeared to be immature (Darling, 1984). Up to 36 gray whales have been counted off the coast of Oregon during the summer (Sumich, 1984). These whales were measured photogrammetrically and the majority were immature. The predominance of immature whales at these two areas is consistent with our observations of summering gray whales being predominantly immature.

Foraging animals were seen during this study, though the prey was not known. Gray whales off Vancouver Island were found to be foraging primarily on mysids associated with kelp beds along the rocky coast (Murison et al.,

1984). Plewes et al. (1985) reported a single gray whale feeding on ghost shrimp (*Callianassacaliforniensis*) and soft shell clam (*Cryptomyacalifornicus*) off Vancouver Island. Oliver and Slattery (1985) found that gray whales in Pachena Bay, Vancouver Island (31 nm from Neah Bay) fed on benthic ampeliscid and other amphipod crustaceans in an environment ecologically analogous to the major feeding areas in the Bering Sea.

Heyning and Dahlheim (in press) found that a high proportion of gray whales that die in other areas have also been yearlings, similar to our findings for Washington. They suggest that the period of first migration for weaned young (yearlings) is a critical period for this species. Heyning and Lewis (in press) reported that most gray whales that became entangled in fishing gear were younger animals, but not calves.

Considerable media attention in recent years has been given to the occurrence and mortality of gray whales in Puget Sound. There has been speculation about whether these animals are lost and about the potential impacts of contaminants. The gray whales we observed in the spring and summer in Puget Sound and the Strait of Juan de Fuca appeared to be foraging, and their prolonged stays in particular areas appeared related to preferred foraging locations. Their presence in the region is consistent with observations of gray whales foraging in the spring and summer off the coast of Oregon (Sumich, 1984) and British Columbia (Darling, 1984).

There is not adequate information to determine the role of pollutants in gray whale mortality. Observed gray whale mortality throughout their range is well below what would be expected given the population size and dynamics (Heyning and Dahlheim, in press). The death of two of six gray whales that we had identified in southern Puget Sound is a high percentage, but the sample is small. Gray whales usually feed along the bottom where they are potentially exposed to elevated contaminants in bottom sediments. The limited previous research on contaminant levels in gray whales has generally revealed low concentrations of contaminants compared to other marine mammals (Wolman and Wilson, 1970; Malins et al., 1984). Elevated levels of aluminum were reported by Malins et al. (1984) but this was from an animal found dead west of Port Angeles, away from likely anthropogenic inputs of contaminants. There was no evidence that this animal had been feeding in Puget Sound or that the levels found were elevated compared to other gray whales.

To better understand the role of contaminants in gray whale mortality will require a coordinated research effort. This should include: 1) tracking the movements and behavior of identified gray whales that enter Puget Sound, 2) rapid examination and sampling of dead gray whales, and 3) analysis of contaminant levels in these animals and those that die away from contaminated areas. Given the annual variability in the number of gray whales that die

in this area, this effort would need to be conducted over multiple years to obtain a large enough sample.

As the gray whale population size increases, we will likely see increasing numbers of gray whales in the Puget Sound region as well as increased numbers of deaths.

ACKNOWLEDGEMENTS

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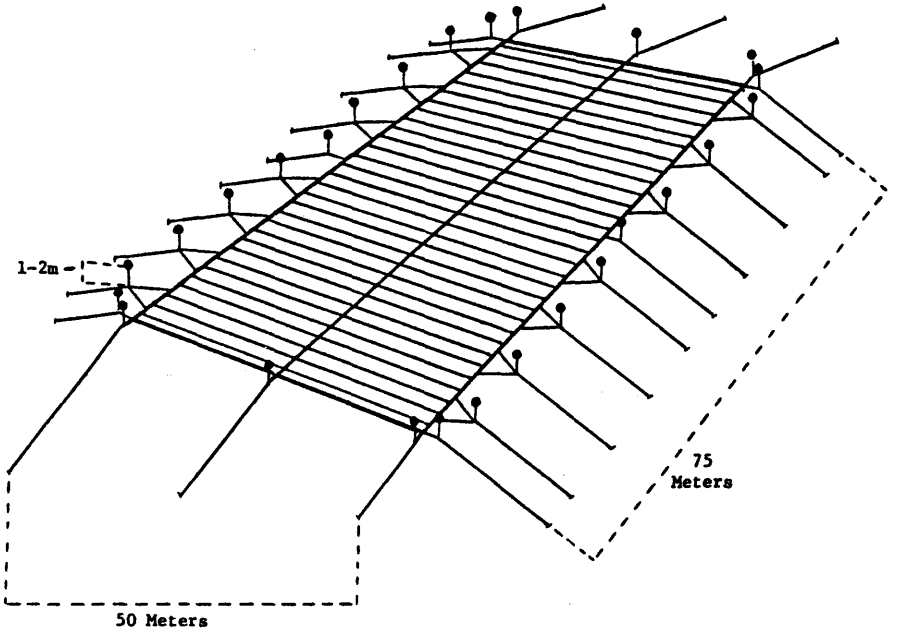

Figure 4.
SET DESIGN FOR KELP DEPLOYMENT. *Total surface area of set, including floats, is approximately 1 acre. Design shows 30 long lines each 50 meters in length. Depth of entire set can be controlled by manipulating the lengths of the float lines. Anchor lines not drawn to scale; typical anchor lines have 5:1 scope (length:depth). Units as small as 1 long-line are easily designed and deployed.*

SUMMARY

We have developed simple and reliable methods for the artificial planting and maintenance of *Nereocystis* and *Macrocystis* kelp forests. Small or large areas can be planted with flexible long-line substrate. We believe that these methods can be widely applied for the purposes of enhancement of marine habitat, remediation of mineral eutrophication, and environmental mitigation. Rapid results are obtainable, thus potentially providing a way to quickly replace critical habitat lost to natural or man-induced disaster.

We have emphasized plantings on artificial substrates such as rope. We also believe that natural or artificial rock substrate can be seeded with kelp either through the direct application of seed-twines, or through secondary settlement from spores released by long-line populations.