PROCEEDINGS

FIRST ANNUAL MEETING ON PUGET SOUND RESEARCH VOLUME 1

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THE FIRST ANNUAL MEETING ON PUGET SOUND RESEARCH

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FOREWORD

Katherine Fletcher
Chair, Puget Sound Water Quality Authority

The First Annual Meeting on Puget Sound Research was held at the Seattle Center on March 18-19, 1988. The meeting was co-sponsored by the 13 agencies, universities, and private firms that are listed in the front of this volume. We are grateful to those organizations for so readily providing support for this meeting. This support made it possible to hold the costs for the meeting registration and proceedings to a level that encouraged broad attendance and participation. The attendance at the meeting--700 paid registrants--speaks strongly of people's interest in the information presented and desire for the exchange of ideas that occurred at the meeting.

Protecting Puget Sound is a complex, long-term task involving many people, substantial funding, and troubling uncertainties. In making a long-term commitment to the Sound's future, it is vital to recognize and fulfill the need for research activities to increase our ability to make good management decisions. As part of a strategy to accomplish this, the Puget Sound Water Quality Authority in its 1987 Puget Sound Water Quality Management Plan specified that an annual meeting on Puget Sound research should be convened.

The purposes of the meeting, as stated in the plan, are to serve the needs of: 1) researchers for scientific exchange and dialogue; 2) regulators, resource managers, and public officials for technical information that would guide them in developing policy; and 3) the public for translation of research results. These are demanding objectives that are difficult to satisfy simultaneously. The meeting steering committee felt that the greatest unmet need that the conference should address was the need for translation and dissemination of research results to agency officials, members of the public, and all those who make decisions about managing the Sound. To help meet this objective the steering committee organized the technical sessions around current issues and questions related to managing the Sound and its watersheds. Session chairs were asked to provide introductory comments and a closing statement that would help link together and provide a perspective on the diverse research papers presented in their session. Speakers were strongly encouraged to address the implications of their research results for the questions that we have in managing the Sound.

The opening session of the meeting was devoted to a presentation of the recommendations of the Authority's Committee on Research in Puget Sound and a panel commentary on those recommendations. Again, the theme of communication and translation of research results, of orienting research toward "actions" or "outcomes," was emphasized. Both the committee and the panelists also expressed a deeper concern and commitment to the principle that research is essential to wise and enlightened decision-making. We cannot afford to operate in ignorance of the potential consequences of

our actions, either for the natural environment or for the economy and communities of the Puget Sound region.

I hope that this meeting will truly be the first annual meeting. There is a need to continue opening the channels of communication between the research community and those of us dispersed in various agencies and offices. The form of the next meeting is not yet decided. It may be a logical next step to convene a series of technical workshops or forums around specific issues. Each workshop would discuss all information available on an issue and attempt to reach a consensus on the status of our knowledge and our next research priorities.

I hope that these proceedings will serve the purpose for which they were intended--to create a permanent record that meeting participants and those not in attendance can refer to as they continue in their own work. I hope that as you read these proceedings you are challenged to reexamine your thinking about Puget Sound.

Finally, it has been said that Puget Sound presents a unique national opportunity for research. There are very few, if any, other estuaries in the country where one has the opportunity to examine the natural environment in a contaminated or perturbed state and, nearby, to study a relatively pristine reference area. We should commit ourselves to maintaining a vigorous research effort that makes use of this natural laboratory for the benefit of our own decision-making and similar efforts around the country.

KEYNOTE ADDRESS

Lawrence J. Jensen*

I appreciate very much the invitation to be with you today at this first annual meeting on research in the Puget Sound. I have to tell you as I stand here and look out at this group, that it is indeed an impressive sight. I think it speaks well of the efforts of the Water Quality Authority and of many other federal, state, and local organizations which have joined forces to meet the environmental challenges in Puget Sound. I think your presence here today in such numbers also bodes well for the future of Puget Sound. I would hope as you go from this meeting and break into your smaller sessions--and particularly as you begin to review the scope, complexity, and the serious nature of some of the challenges that we face here--that you would remember the strength of this group.

I think all too often, as we get involved in our work and as we look ahead at how much there is to do, we tend to forget just how far we have come. I am reminded that it's been just sixteen years since the Clean Water Act became law, and that's really not a very long period of time. Yet in that period of time we've succeeded in permitting some 90 thousand dischargers nationwide; we've built over five thousand waste water treatment plants; invested over $200 billion in various water pollution control efforts; and maybe even more importantly, we find as we look across the country that in every state we have strong institutions with skilled, experienced water quality professionals. You have in the citizenry at large, I think, a consciousness about clean water issues. All of this has come about in what is really a relatively short period of time.

I would hope that you would bear that in mind as you continue your efforts here in Puget Sound. I would love to come to back to the fifth or the tenth annual meeting. I think all of us will be pleasantly surprised at how much we've accomplished in those years.

It's important to keep that type of perspective when we think about water quality problems. The challenges that we face are immense, and they do pose some very difficult problems for us. This morning I would like to offer a perspective on the importance and the significance of the work that you are doing here in Puget Sound as I see it from a national scale.

First, let me briefly describe for you how the work that you are doing here in Puget Sound fits into a much larger effort nationwide that is focussed on estuarine waters and near-coastal waters, the values of those resources, and the environmental challenges that they face. I came to Washington to

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participate yesterday in a ceremony which officially designated Puget Sound as part of the National Estuary Program. A year ago in the amendments to the Clean Water Act, Congress gave the Administrator the authority to work with the states in designating estuaries of national significance. Together with the states, they were given authority to convene management conferences that would pull together state, federal, and local interests and help and support them in their efforts to focus in a comprehensive fashion on the challenges that we face in protecting our estuarine waters. Yesterday was Puget Sound. Last week I was in Providence, Rhode Island, and there we designated Narragansett Bay as part of the National Estuary Program. In November I travelled to Elizabeth City in North Carolina and we designated Albermarle Pamlico Sound as part of the estuary program. In January I was in Cape Cod; there we designated Buzzard's Bay as part of the program. Next week I travel to Long Island and will participate in a ceremony designating Long Island as part of the estuary program. Next month will be San Francisco Bay. Before the year is out we are hopeful that we will be participating in and supporting as a federal government and as the Environmental Protection Agency a dozen estuary projects nationwide.

We've begun just recently what we call a Gulf Initiative, taking on what may be our largest estuarine challenge, the Gulf of Mexico. We're beginning to search for ways to pull together all of the varied people and organizations that are interested in addressing some of the problems that we face there. In December I travelled to Baltimore and participated in a ceremony at which the Administrator of the Environmental Protection Agency was present and also the governors of three states. There they signed a second Chesapeake Bay Agreement, building on their efforts from the past three or four years which have been largely research and assessment. In December those governments committed themselves to some very specific and some very challenging goals as far as addressing the problems in the Chesapeake Bay. In the Great Lakes we find similarly a renewed commitment to taking the actions necessary to preserve the environmental health of the Great Lakes. And so, you can see that you're part of a growing and intense focus on estuarine and near-coastal waters across the country--one which is beginning to gain momentum and energy. So you're not alone.

You should also recognize as you talk about the problems here in Puget Sound, the ones peculiar to the place where you live, that you also have much to share with those estuary projects that are organizing themselves nationwide. I think Puget Sound in many ways is a leader in marking the way for how we can organize ourselves to address the estuarine problems. The fact that you've established a separate Water Quality Authority, charged by the state government with the authority to plan and coordinate and your cigarette tax, part of which is dedicated to the clean up of the Sound--these are important indications of the strength of the commitment here in Puget Sound.

We have been able to take your experience and help others as they begin similar efforts across the country. I would hope, as you focus on specific details of the problems that you face here that you would recognize that you are part of a much larger effort. The contributions you make here, important as they are for the health of Puget Sound, will often also have application and bring benefit to similar problems that we face in other estuaries across the country.

That's a perspective on how Puget Sound and its estuary program fits into the national effort. Now let me step back for a moment, and give you a perspective on how your efforts here fit into the larger national effort to address water pollution, not just in the estuarine areas, but in our surface waters across the country and even in our groundwater resources. Last year, in February of 1987, the Clean Water Act was amended. This was not the first, but I think perhaps the most significant set of amendments that have been added to the Clean Water Act since its passage in 1972. It marked a very significant change in the focus, direction, and thrust of our national water pollution control efforts.

We're moving, partly as a result of those amendments and partly as a result of successes we've had over the past 15 years, from a national water pollution control effort that was primarily point source-focused to a program that is focused on all sources of water pollution. The point source program was driven by technology-based controls and was predominantly federal, both in the financial resources that were available and also in many of the requirements which Congress placed upon the states and the local communities from a national level. We are moving to a program that is dealing not so much with technology-based controls but with water quality-based controls. It is not so much dominated by the presence of the federal government as it is led by the state and the initiative of local governments.

Over the last 15 years our focus generally has been on point sources--on the discharges from the factories and industries of America and on the discharges of municipal sewage from our cities. It hasn't been exclusive, but that has certainly been the primary focus of our efforts. The effort to put in place a set of controls on those types of discharges is drawing to a close. We find as we look across the country that there is really a remarkably high compliance rate by our major industries with the requirements of the Clean Water Act. And we're finding as well, largely as result of the concentrated efforts we've made over the last four years, that in controlling municipal discharges we've done a nice piece of work. We found four years ago, when we looked at the municipalities, that there were still, 10 years after the Clean Water Act was passed, some 1500 major municipalities across the country that were not in compliance with the basic secondary treatment requirements of the Act. As a result, we put together an effort in cooperation with the states to focus on that universe of cities. I'm pleased to report that as we approach the deadline which we set for July 1, 1988, we're finding all but a handful of that universe of 1500 municipalities are either in compliance with those secondary treatment requirements or are on schedules that will soon bring them into compliance. So we're reaching a point, speaking broadly, where that major effort to get appropriate controls on those large and obvious sources of waste water discharge into our streams, lakes, and rivers is coming to an end.

We begin now to lift our heads from that work and focus on the challenges that remain. What do we find? Something that won't surprise you; something I think you've learned from your efforts here in Puget Sound. There is a whole category of sources out there--nonpoint sources--which are significant contributors to pollution in the waters of the United States. We have to build a program that focuses much more than it has in the past on all sources instead of just point sources. Congress recognized that in the

amendments to the Clean Water Act. It required the states to assess over a very short time period (by August of this year) the nonpoint source pollution in each state that is causing actual water quality problems that need to be addressed. Having made that assessment and identified those problems, the states are charged with the responsibility of putting together a nonpoint source strategy. This strategy is a plan that tells how the state will move forward to address its nonpoint source problems. Obviously your efforts here in the Puget Sound are an important part of the state of Washington's efforts to make that assessment and to develop that strategy, and it reflects the change in focus from a predominantly point source program to one that focuses on all sources.

At the same time we're moving from an emphasis on technology-based controls to water quality-based controls. We have said in the past to the dischargers across the country, "You can only discharge wastewater into our rivers and streams if you have first ensured that you have cleaned up the wastewater to the maximum extent possible. Whatever is technically feasible is required of you before you can discharge your wastewater into our rivers and streams." In other words, to a certain extent, we haven't focused on the actual water quality in the streams. We have required as a first line of defense that we get those technology-based controls in place. Now what is contemplated by the Clean Water Act is that we move to a water quality-based focus, where we put on our hip boots, go out into the middle of the stream and assess the actual water quality to determine whether those technology-based controls are adequate to protect the uses that we would like to make of our water resources in the country. From my perspective, that move towards water quality-based controls puts a premium on the type of work that you do--on the research effort, on good science--because the problems that we will face are complex and challenging in determining what water quality-based controls are necessary to ensure the purity of our water.

Finally, we're moving from a program that has been federally dominated to one that is much more led by the states. The nonpoint source effort I mentioned to you is an example. Congress recognized the strong institutions that we have in the states and gave them the responsibility of telling us how nonpoint problems are to be solved. You see in a number of areas under the Clean Water Act the initiative being given to the states for setting the agenda for the next several years as we address our water quality problems.

I hope that's not too much of an oversimplification, but I hope it gives you some sense of the shift that is taking place in the national perspective in our water pollution control efforts. As you reflect on what is taking place here in Puget Sound you will recognize, I hope, that the effort here is really a microcosm of that shift. As I read the assessments that you've done of the problems that you face here, it's clear that you recognize the contribution made not only by point sources, but by nonpoint sources as well. It's clear that you have made substantial strides in focusing on the actual water quality in the Sound. I think you find here in Puget Sound an excellent example of initiative being taken by a state and the leadership role being assumed by a state in addressing the water pollution problems that it faces.

By way of giving you perspective, I'll conclude with one final thought as you begin your sessions today. Last fall there was a little noticed news item having to do with the Bureau of Reclamation. It was little noticed, and yet

highly significant, in giving us a sense, particularly here in the western United States, of what the focus will be as far as our water resources in the years to come. The news article dealt with the Bureau of Reclamation, which has long been the water czar in the West, charged by federal law with the responsibility of building the large dams and developing the irrigation projects which brought the West to life. It was noted in that article that the Bureau of Reclamation itself had come to a recognition that that era of water resource development, of large irrigation projects and huge dams, was drawing to a close, and they needed to find for themselves a new sense of mission. I was interested to note that heading the list of things which the Bureau of Reclamation sees itself as doing in the years to come is a focus on water quality. I found it very significant for the Bureau of Reclamation to come to that recognition. In the last hundred years one of the driving efforts in the western United States has been that reclamation effort--the effort of reclaiming land from nature, from desert conditions and from uncontrolled rivers--so that it can be farmed and so that communities could grow up around it.

I suggest to you that as important as that effort has been, there is a much more important effort of which you are a part today. Over the next 10, 20, or 30 years it won't be the reclamation laws authorizing the building of dams that will be the focus of our efforts in water here in the Western states. It will be the reclamation laws known as the Clean Water Act or the Safe Drinking Water Act--the water laws which charge us not with the responsibility of reclaiming the land from nature, but reclaiming our water resources from man, from the pollution and degradation that by virtue of our activities we visited upon them. I think that will be the significant reclamation effort of the years to come. I'm pleased to be a part of it. It's really encouraging to me to be in a meeting like this today with as many people as are here who are also interested in being a part of that reclamation effort. I wish you well. Thank you again for allowing me to join with you in this important meeting.

SUMMARY
FINAL REPORT
COMMITTEE ON RESEARCH IN PUGET SOUND

David W. Jamison, Megan Dethier, and John Strand*

Mandate for the Committee on Research in Puget Sound

In 1986 the Puget Sound Water Quality Authority reviewed the Puget Sound research effort and identified several issues that needed to be addressed. Among these issues were the planning, coordination, and funding of research and the access to and use of research results by decision-makers. In the 1987 Puget Sound Water Quality Management Plan the Authority established the Committee on Research in Puget Sound and asked the Committee to make recommendations to the Authority on these issues.

The Committee was formed in February 1987. It is composed of 20 individuals representing academic institutions, state and federal agencies, the business community, agriculture, environmental groups, and private research organizations. This report presents the findings and recommendations of the Committee. The recommendations will be presented for comment and discussion by participants at the First Annual Meeting on Puget Sound Research, which will be convened in Seattle on March 18 and 19, 1988.

Findings of the Committee

The Committee finds that there is no comprehensive and coordinated program for research on Puget Sound. While various federal agencies currently support most of the Puget Sound research, each agency must give first priority to meeting its own needs. None of these agencies claims responsibility for Puget Sound as a whole. Consequently, the scope of the research is limited. State agencies generally have limited budgets that usually can only support short-term and site-specific studies. The result of this fragmented approach is:

1) There is limited coordination among agencies to optimize how research dollars are spent;

2) No planning activity identifies the research needs for the whole Sound as a complex system and sets these in the context of the most urgent and serious problems;

3) There is no stable and continuous source of support for research questions that require a long-term effort; and

*Jamison is chair of the Committee on Research in Puget Sound. Dethier is chair of the Subcommittee on Establishing Research Priorities. Strand is chair of the Subcommittee on Institutional Issues.

4) There is little research that looks at the cumulative effects of our decisions on the Puget Sound system as a whole.

5) There is no medium for interaction among researchers to discuss the results and the implications of their work.

The Committee also finds that the present system falls short of delivering the research results to the decision-makers and other involved parties in a form and time frame that allows the results to be used in decisions. A significant percentage of agency-sponsored research resides in internal reports that receive limited distribution. Agency managers have little opportunity to stay abreast of the multiple professional journals that might contain Puget Sound-related research. Staff at the local planning level have a particularly strong need for research results that are translated into operating guidelines or models that they can readily adapt to their specific circumstances.

Research Priorities for Puget Sound

The Committee developed a process to produce a comprehensive list of research priorities for Puget Sound and used the process to develop the list of priorities that is included in this report. The process was keyed to using the information needs of decision-makers and managers as the starting point for identifying research priorities. Work groups of technical experts were convened to take the information needs of the managers and refine and translate these into the research that is appropriate to address those needs. After considering the recommendations of the work groups, the final list was compiled by the Committee. It includes research priorities in six major research areas:

1) The distribution and physical/chemical factors related to toxic chemicals;

2) Biological effects of toxic chemicals;

3) Habitat modification;

4) Conventional pollutants and nutrients;

5) Microbiological contamination; and

6) Environmental and regulatory policy.

Institutional Issues Related to Research

The Committee concluded that the magnitude of the problems related to coordination, funding, and application of research results requires an institutional structure to achieve the research goals identified by the Committee. Policy changes alone cannot accomplish this. The Committee identified seven functions that would need to be carried out by this institution:

1) Managing a process to set research priorities;

2) Generating research funding;

3) Managing a research grants program;

4) Translating and disseminating research results;

5) Facilitating access to data;

6) Coordinating with the Puget Sound Ambient Monitoring Program; and

7) Providing recommendations on the establishment of research reserves.

Existing Puget Sound institutions and institutions in other coastal areas were examined to see if they could provide models for the functions outlined. In its review the Committee looked for several critical characteristics:

1) Participation in the process for setting research priorities by all the parties involved in decisions to manage the Sound;

2) An ability to generate substantial new funding that is regionally (not federally) controlled;

3) An ability to communicate research results from an unbiased position;

4) A primary focus on Puget Sound; and

5) Independence from the programmatic and policy influence of a single agency or entity.

<u>A Proposal for the Puget Sound Research Foundation</u>

The Committee proposes creation of a new institutional structure that combines many of the desirable features of other model institutions. The Puget Sound Research Foundation is proposed as an independent nonprofit corporation consisting of representatives of colleges and universities, government agencies, industry, tribes, citizens' groups and nonprofit foundations. An appointed board of trustees would oversee management of the Foundation and would be responsible for fund raising to generate broad-based support for the research program. A scientific council composed of 12 scientists familiar with Puget Sound would be responsible for identifying and ranking research needs for Puget Sound and for reviewing and ranking proposals for research funding. A management council would be composed of representatives of the key agencies and jurisdictions involved in Puget Sound management decisions. This council would provide the primary avenue for input of management needs to the scientific council in setting research priorities and coordination with the Foundation's research grants program in implementing and funding the final list of research priorities.

The proposed Puget Sound Research Foundation provides, for the first time, a mechanism to coordinate research priorities that cuts across the issue- or mission-specific perspective of any one group or agency and focuses on the entirety of Puget Sound. This approach will help ensure that the resources that are devoted to research are focused on the most important problems for the protection of the Sound. The improved information base generated by this effort will provide agencies with the tools they need to make realistic and defensible regulatory decisions. Reducing regulatory uncertainty reduces

the cost and time spent in litigation for all parties.

Through its research grants program the Foundation will fill gaps in ongoing agency research and will serve as a regional sponsor for innovative research that has potential for long-term benefits for Puget Sound. Finally, the Foundation will serve a translation and dissemination role, assisting in the publication of research results and in making research a tool in helping to resolve present and future problems in Puget Sound.

PANEL DISCUSSION OF COMMITTEE REPORT

Kai N. Lee[1], G. Ross Heath[2], James C. Waldo[3], Phil Talmadge[4]*

KAI N. LEE

This morning, to begin the process of discussing the research plan, the Authority has assembled a group that has two scientists and two lawyers. That may be an indication of the kind of discussion we should be sparking. It is important that this is the first annual research conference, signalling not only the optimism of the Authority, but the lateness of the time at which we have come to think of Puget Sound as a unit to be examined.

The Authority was formed in 1983 in order to do something called cleaning up Puget Sound. It isn't so clear what it means to clean up Puget Sound, it isn't even clear what Puget Sound is. Dave Jamison made a very important point this morning, that there is today no perspective on what the whole Sound as an ecosystem is and how it operates. You heard later from Megan Dethier that in this process of narrowing down to specific research questions, such as the transport of toxins, the panel preparing this plan deliberately avoided a whole Sound perspective. The reason that we don't have a whole Sound perspective is fairly clear when you stop a moment to think about it. While the work of the Authority is the work of planning and coordination, the basic dilemma of public policy is that planning tends to aggregate things but implementation tends to disaggregate or to decentralize action. As we heard Mr. Jensen say in his keynote remarks, implementation of the Puget Sound Management Plan is going to require disaggregation in the future.

We face a future where "cautious creativity" is going to have to be the watchword. We need to emphasize stewardship of what remains of the natural resources of the Sound as well as a cautious approach to making use of those resources in our human activities. The future that we face is one that will not be as intensive in its use of technology as has been the case in the past. The final commitment to secondary treatment in our municipal sewage treatment programs is really the end of an era. What we see in the future are more management orientations, more uses of the voluntary activities of hundreds and thousands of people and smaller organizations, rather than the building of large concrete structures. We will not, therefore, have a need or source for high capital investment dollars, but that doesn't mean that money isn't still critical. It is in that kind of context, where we are moving away from technology and away from federally provided funding, that we need to think about the problem of managing the Sound and the scientific problem that lies behind it.

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I spoke a moment ago of cautious creativity. I think if we look to the future what the research plan attempts to do is to lay out some directions and priorities for what might be called "directed creativity." Directed creativity is, as every parent is aware of with respect to one's children, an oxymoron. What can be directed and what can be created are often not in the same direction at all. It is especially an oxymoron when it comes to the question of research, where the need of managers to have questions answered only accidentally and rarely corresponds with the scientific agenda that is before the research community. The dilemma of managing directed creativity is the heart of the idea that is addressed by the Puget Sound Research Foundation concept that was laid before us a few minutes ago.

G. ROSS HEATH

I'm not going to be able to comment on all the scientific issues in the report. I'm hopeful that the discussions that we will have in the next couple of days will start doing that much more seriously than any speaker can do in an introductory session.

I'd like to congratulate both the Authority and the Committee on Research for the job they have done in recognizing the importance of research in an activity like the management of the quality of Puget Sound. It might seem obvious in a society that values education and scientific research as highly as this one does that there would be widespread acceptance of the concept that management on the basis of knowledge is better than management on the basis of ignorance. However, one doesn't have to look very far in this country to discover all kinds of examples where that has clearly been demonstrated not to be the case. I think it's very healthy that the Puget Sound Water Quality Authority has started out with that philosophy in mind.

One of the issues I think that always comes up when one raises the term research is the disagreement, sometimes conflict, between whether one should give high priority to applied or basic research; and in fact, what does one gain from the two. Jim Waldo has pointed out in situations like this there is really no difference between applied and basic research; all research is applied. The issue is really the degree to which the research is directed. I think agencies in particular are more comfortable with research where they know the question, and they have a pretty good idea of how to go about attacking it. In that case they can write a pretty precise RFP and go out and find somebody to do the work. The kind of thing that comes to mind in that regard is how widely a given pollutant is dispersed within the Sound. We know how to measure it, we know enough about statistics to design a sampling program; it is possible to direct that research very substantially.

It is much more difficult for an organization to deal with the non-directed types of research. These are issues where we recognize the problem, but we really don't have a very good idea of how to go about solving it. One might look at something like the tumors we find in sole in various areas of the Sound. The question might be, why do these fish get these tumors? That opens up a whole raft of issues such as: should we be looking at specific pollutants, is there some aspect of the life cycle that is particularly sensitive? There are many, many angles to follow, and none of them is obviously likely to be more valuable or provide a more conclusive answer than any other. Therefore, one has to ask the question in a much more open way,

accept proposals to do the work in a much more open way, and recognize the chance of failure is quite high. I would say it is important when the research activities get under way that they don't just fund sure things but they do make sure that they fund at least a significant number of high risk exercises that could be high payoff. That is much of what basic research can do.

Another issue that is mentioned in the report is the importance of peer review. Unless the research is independently looked at by somebody who has no vested interest in the design of the experiment or the way that it was carried out, there will always be questions as to its validity. Scientifically this has always been viewed as very important. More recently it has started to appear in the courts that research which has been peer reviewed and has appeared in the peer reviewed literature is given much greater credence than research which is sponsored by a particular organization and is either done by that organization itself or by its contractors and then simply disappears into the files. That kind of research doesn't have nearly the credibility, either legally or scientifically, of well-reviewed work. Whatever organization is finally set up here, you should place very great emphasis on peer review.

The research report spends quite a bit of time talking about the proposed Puget Sound Research Foundation. I must admit that my initial response to the creation of yet another bureaucracy was something akin to horror. But I do recognize that there are some functions which are not now being done well. I would urge the committee to separate the functions from the operations and to think carefully whether they couldn't economize by forming the Foundation but using one of the many existing operations in the Puget Sound area to handle a lot of the logistics, which otherwise are very costly for a new organization.

I agree with the comment that it is important that this Foundation have an independent source of funding. The objective of getting an endowment rather than having to go back to the legislature every session is a very important one. The kinds of problems we are looking at are going to take many years, and in some cases many decades, to solve. It has been demonstrated over and over again that agencies and political interests just don't have those kinds of lifetimes. The successful models that have been talked about do have some core of permanent funding that belongs to them, that they can focus on the problem without having to fight every year. As a strategic point, before formally setting up this kind of organization one should have in sight a budget on the order of $3 million. If the Foundation is set up without some additional clear-cut support, then the staff is going to find itself continually fighting to survive rather than fighting to attack the important problems that are its real objective.

Finally, my impression of the research report is that it is an important first step, but it still strikes one as too broad. I would estimate that the list of research priorities represents many tens of millions and probably a couple of hundred million dollars worth of costs. Since that amount of money will probably not be immediately available for research on Puget Sound, the committee is going to have to get the managers, agency people, and those who are involved in the health of the Sound together with a moderator to distill out the priorities. There are two kinds of priorities that should be considered: priorities in terms of importance (what are the things we need to

know right now that will give us the most benefit if we do them) and priorities in time (which things are important problems where a delay of five years is going to make a big difference). I think breaking the list of priorities into priorities in time and priorities in immediate importance would be a very important next role for the committee.

JAMES C. WALDO

I speak as a fan of the institutional concept in the report and in that vein I am also going to be fairly direct and in some respects critical. I think that this effort is more likely to fail than to succeed if it is not carefully and precisely thought out. I read the report several times and I encourage everyone to read the summary and then ask yourself the question, does that summary compel you to reach for your checkbook to fill out a check? If it doesn't, then it may not get the appropriate response at the state level or the federal level or the private level; and a necessary tool that we all need will not happen. I want to speak from the position of someone who might be approached to fund this, because that in some ways tends to sharpen your thinking. As I read the report I agree with its conclusions, and I agree that it points up our failure as a society to adjust our institutions to solve this problem. But we will never have enough information to make us all feel comfortable. We will never have enough information at the time when we will be forced to make decisions. We will always sin either by taking action when people say we have insufficient information or not acting because we claim we don't have enough. I submit that there will never be sufficient, necessary, stable and continuous support for research on the magnitude that we would all like to have. So, the question then is how do we move in the direction that the report sets out to accomplish those goals and to rectify some of the areas where we are not currently doing a good enough job?

We are starting such an effort in a very difficult financial climate. It is difficult at the state level, at the federal level, with private companies, and with foundations. We probably will have a recession sometime in the next two to three years, and that will make financing an effort like this even more difficult than it is in better times. On the other hand, it is clear that the people of this state want to see improvements in terms of correcting past environmental problems and ensuring that such things do not occur in the future. They have evidenced time after time in many ways that they are willing to pay for that, provided there are results. I think that agencies that work in and around these areas want successes, they want to be able to demonstrate that they are making a difference. Those who are affected by these decisions, whether they are in the environmental community, the business community, agriculture, fisheries, or local government also want to see results.

For purposes of discussion, I would retitle the name of this organization to the Puget Sound Management Information and Scientific Research Foundation. First, it needs to be part of a system, not a stand-alone entity. Second, it needs to be targeted to actions and outcomes. The question is, what are you trying to get at and what actions could it lead to if you had the information?

In terms of making more effective use of our scientific and research resources, we do need to prioritize and direct at least a portion of those efforts. The dialogue between the managers and scientists and the research

community ought not to be all or nothing. How can we direct a portion of these efforts specifically to Puget Sound and specifically to helping us make a difference?

There is a need for greater scientific interchange and scientific credibility. We are finding increasingly that everybody is bringing their experts to a dispute; and after all the experts have testified, it is less clear what we ought to do than it was when we started initially. We are going to waste a lot of money and time if this process does not try to foster and help support collaborative research. This includes not only peer review, but also help in designing priorities and addressing issues such as: how are the studies going to be cast, what is the form of the research, and can a broad group of the scientific community subscribe to it?

The goals can be stated in the form of two questions: 1) how do we get the best information possible to decision-makers in a timely fashion; and 2) when will we have better information, at what cost, and how does that affect the nature of the decisions we have to make today versus those that can wait until we have better information?

An action and outcome orientation and an emphasis on collaborative effort are in this report but haven't been sufficiently crystallized. If they were, it would give you the ability to go to the state and federal government and private funders and say, here are the decisions that are critical to us in Puget Sound from an environmental point of view, from a societal point of view, and from an economic point of view. Without this information we either will make no decisions and stall, while everybody fights various procedural battles, or we will make poor decisions. Poor decisions mean that we may require less than is required to protect the environment, or we may require costs that are unnecessary. Imprecision is the enemy of all of us who care about Puget Sound, who want an environment and a sufficient economic base for people to be able to earn a living.

How do we get there? My view is this report probably puts us at the leading edge of these kinds of efforts in the country. That is both a very positive statement about the report and in some ways a criticism of the efforts that have gone on elsewhere in the country, where they have been satisfied with less than precise thinking and simply launched these efforts. In my view some of them have wasted a lot of money for the results they have obtained.

Money is essential to this effort. The money will come out of enlightened self-interest on the part of governmental agencies and private folks. A program should address how this research over some period of time will help them do a better job at the decisions that they have to make as they affect Puget Sound. The test should be action outcomes not a list of desired research. When I read the list of research priorities that were in this report, I was unable to determine what would happen when that research was completed. So as a funder, I'm not sure what I am buying other than a lot of good research. Good research is a worthy goal, it just happens to compete with a lot of other worthy goals in today's society, and that is not necessarily enough.

Finally, as to the endowment, let me suggest that endowments are earned, not given. Obtaining an endowment should be a long-term not an immediate goal

of the organization. You first need to go out for a period of years and do high quality work that leads to results. Then when you go for an endowment, you can say, this is what we have done; now if we can have a better, more predictable, more stable base, we can do a lot more. I think this should be viewed as an evolution that should occur over an extended period of time, not an all or nothing proposition as of today.

PHIL TALMADGE

The reaction that I had to the report was a very positive one on several different levels. As to the prioritization of research activities, I think it is something that is long overdue, and it was something that we envisioned when the Puget Sound Water Quality Authority was first put into place. My only quarrel with the list of priorities is that when you put environmental and regulatory policy as number 6 for a research foundation whose principal function is going to be affecting environmental and regulatory policy, that is a mistake. The first five items of priority are significant and should be considered in the priority in which they are set forth, but environmental and regulatory policy should be a part of each and every one of those prior five items. Then the legislature, or whoever will be using the research, will have the opportunity to have that research affect public policy. That is, in my view, the first and foremost focus of the research activities of such an entity.

My second comment relates to the question of whether this research function should be conducted independently of existing institutions. By way of history you should know that research foundations or research institutes have been proposed in prior sessions of the legislature. They have been proposed as an adjunct to the activities of the University of Washington, and, unfortunately, for one reason or another, the legislature felt that having a research entity at the University of Washington was unacceptable. The legislature apparently thought that some more independent structure would be appropriate, something independent of the University of Washington or any other existing institution. Therefore, from what I can see of the history of research related activities, it would be very useful to have the research function conducted by an independent foundation that is separately funded from a variety of sources, rather than just the legislature itself. Its opportunity for success, its opportunity to avoid cataclysmic cutoff of funding by one level of government or one organization or another is certainly more realistic.

The last thing I want to mention is the question of whether or not we really are operating in an environment of enlightened self-interest or in a situation where the policy makers want information upon which to make management decisions. I think research is absolutely critical to the policy making function, and we have operated in many instances in Olympia, Washington, D.C., and elsewhere in a vacuum when it comes to information about the issues on which we are attempting to make policy. The difficulty I see is that we have not had the kind of broad-based public support for Puget Sound activities that some people would like to think that we have had. It has been suggested that the people of the state of Washington and the Puget Sound basin have a deep and abiding commitment to cleaning up Puget Sound and have a deep and abiding commitment to funding appropriate management of the resources of Puget Sound. Unfortunately, over the last two or three years, from my direct observation of the legislative process, that assertion is

not true.

In the last session of the legislature, legislation the Puget Sound Water Quality Authority proposed did not pass the legislature. This includes legislation that would have provided for criminal penalties in some circumstances where people violate water related laws, efforts to provide money for nonpoint pollution cleanup, and efforts to deal with septic tanks. The legislature, despite the Cigarette Tax that some people are privileged to pay, has not been exactly generous in its funding in this particular area, notwithstanding the knowledge that many of these issues about which we speak are very expensive. Until the effort that we are talking about with respect to Puget Sound digs deeper into the soul of people in Puget Sound by way of citizen-related grass-roots activities, we are not going to be successful in dealing with the management issues, the funding issues, or even the research issues this report talks about. It is my view that we can have a Puget Sound Water Quality Authority, we can have efforts in the legislature, we can have efforts of the sort that this conference represents, but we are going to have to broaden the effort to the citizenry at large on the issue of Puget Sound to really make it possible for pressure to be exerted on the public decision making bodies to come up with the money to make the policy, and to make the tough choices that are necessary. The research provided by a research foundation can assist us in giving information to policy makers upon which to base the tough decisions, but there has to be a broad base of public support for that effort. Unfortunately, over the last couple of years it has not been present. The money will not follow and the tough decision making will not follow from policy makers until that occurs.

KAI N. LEE

I would like to add to the things that have been said, going back to Ross Heath's theme of managing in the face of ignorance. The scientific community is inclined to think that something should not be relied upon until it has been established as a firm finding. Dave Jamison referred to this as the conflict between trying to provide timely information and trying to provide peer reviewed information. As all four of us have implied in our remarks, it is often the case that society acts without having all the information that might be desirable. One of the important functions of the scientific community is to point out areas where certainty is not available, not because nobody has looked, but because the questions are very difficult to answer. Puget Sound bristles with questions of that kind. The most significant knowledge that we have about Puget Sound comes not through scientific research, but through the activities of people making use of the resources of the Sound. As we look to the future it seems to me that an important research opportunity, an important opportunity for learning about the magnitude of and reducing our ignorance, lies in focusing on actual uses and on management steps taken in the Sound. Then we learn from our own experience in a disciplined and systematic way, something that we do not do today.

There has been a lot of quarrelling about what ought to be done with the disposal of dredge spoils off the Port of Everett in preparation for the new Navy Base there. This is an important occasion to learn about dredge spoil disposal, something that can only be done in a limited way because of funding constraints.

We have had a decade and a half of trying to manage fisheries in the Sound in light of the newly interpreted Indian treaty rights. What are the lessons from that kind of change in man's interaction with the biological populations, and what impact does that have on upland watersheds and the need to protect spawning grounds for salmon and steelhead? Those are the kinds of questions which are important to learn, not from laboratory research, but from the laboratory that is the Sound itself.

Puget Sound is no longer a wilderness. It is the setting for a large industrial society. We do not need to choose whether Puget Sound should be a sewer or a playground; we don't need to choose whether Puget Sound should be a highway or an aquaculture tank; we don't need to choose whether Puget Sound is a factory or a scenic treasure. We can have all of those things if we find a way to define our uses and manage our own behavior so we can sustain those uses.

HISTORICAL TRENDS

WHAT DO THEY TELL US ABOUT THE PAST AND FUTURE CONDITION OF PUGET SOUND?

Curtis C. Ebbesmeyer,
Evans-Hamilton, Inc.
Session Chair

Introductory Statement

Curtis C. Ebbesmeyer*

The eight papers comprising this session present a number of historical perspectives of Puget Sound's temporal variability. The first three papers focus on contamination, the fourth on physical oceanography, and the last four on marine life. To aid the reader brief overviews of the papers are given below. The authors' names are followed by the approximate years examined in their work.

1) Crecelius+ and Curl (1850-1980): temporal trends of contamination inferred from the chemical composition of age-dated sediment cores from central Puget Sound.
2) Brown+, Maguire, Armstrong, and Duxbury (1955-1985): historical changes of Puget Sound water quality.
3) Maguire, Brown+, Wilson, and Armstrong (1893-1987): contamination problems in nonurban areas of Puget Sound from interpretations of existing information.
4) Ebbesmeyer+, Coomes, Cox, Cannon, and Bretschneider (1916-1987): long-term changes of the circulation in central Puget Sound related to coastal and mountain conditions.
5) Mearns+ (1900-1987): review of unusual occurrences of conspicuous marine life along the Pacific Northwest coast and in Puget Sound.
6) Nichols+ (1963-1986): variations of deep (200 m) benthic communities in central Puget Sound.
7) Bargmann+ (1948-1987): abundance of economically important marine fish in Puget Sound.
8) Moulton and Miller+ (1949-1988): analysis of long-term changes in Puget Sound marine fishes based on available data.

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+Speaker

Temporal Trends of Contamination Recorded in Sediments of Puget Sound

Eric A. Crecelius[1]
Herbert C. Curl, Jr.[2]

Introduction

Puget Sound has been used for a waste disposal site for more than 100 years. Since the establishment of communities and industry on the shores of the Sound during the second half of the 19th century, the Sound has received a variety of wastes, including municipal sewage, industrial waste water, coal combustion waste, storm water runoff, and particles from metal smelters. The residence time (flushing rate) for seawater in the Sound is about half a year (Ebbesmeyer et al., 1984) while the residence time of particles in the water column is generally less than a month (Baker, 1984; Bates et al., 1987). Some of the contaminants discharged to the Sound are either attached to particulate matter or sequestered by suspended sediments and accumulate in the fine-grain sediments. Those contaminants which tend to remain dissolved in seawater, such as Arsenic (As), Cadmiium (Cd), Copper (Cu), and Zinc (Zn), are transported out of Puget Sounds into the Pacific Ocean (Crecelius et al., 1975, Romberg et al. 1984; Paulson et al., in press).

This paper discusses the temporal trends of contamination that can be inferred from the chemical composition of age-dated sediment cores from central Puget Sound. The fine-grain sediment (less than 10% sand) of the deep region (>150 m) of central Puget Sound, which accumulates relatively undisturbed sediment at a rate of approximately 1 cm per year, provides a useful record of the history of contamination.

Methods

This paper draws upon data from several publications on the distribution of contaminants in age-dated sediment cores collected from central Puget Sound. The intent of this paper is to summarize temporal trends for a variety of contaminants, but not to review or discuss all available data.

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Results and Discussion

Heavy metals

Temporal trends in the mean concentrations of lead (Pb), Cu, mercury (Hg), Cd, and silver (Ag) for nine age-dated sediment cores from central Puget Sound are shown in Figure 1 and 2. Details on sampling locations, methods and chemical analyses are described by Bloom and Crecelius (1987).

The major features of all these heavy metal profiles, except Cd, are the concentration increases that began during the years 1880-1890, reached a maximum in the 1950s, and in the case of Pb, Ag, and Hg, appear to have decreased in the last 10-20 years. The apparent trend of decreasing metal concentrations in Puget Sound sediment deposited after 1955 was tested and determined to be statistically significant only for Hg and Pb. No significant change in the concentrations of Cu, or Cd has occurred in the last several decades. The mean concentration of Pb decreased 12% between 1955 and 1981. The mean concentration of Hg decreased 20% between the 1950s and 1970s. Silver decreased only 8% since the late 1960s. Copper shows no significant change during the last three decades; cadmium exhibits no significant change over the entire length of these cores. In contrast, sediment cores from urban embayments in Puget Sound indicate, that in relatively shallow areas near contaminant sources, there has been a history of Cd contamination in addition to other heavy metals (Crecelius et al., 1984; Crecelius, et al., 1985).

The major feature in the metal profiles (Figs. 1 and 2) is the almost linear increase in the concentrations of Pb, Cu, Ag, and Hg that began at background concentrations in the late 1800s and reached a maximum in the middle of the 1900s. This increase roughly parallels the population growth in the Seattle-Tacoma area. Industrial development began about the turn of the century along the shores of Puget Sound. The ASARCO lead-copper smelter began operating in 1889 near Tacoma. Coal particles in sediments deposited during the early 1900s probably resulted from coal shipping when Tacoma was a major coal shipping port (Furlong and Carpenter, 1982). Anthropogenic increases in the concentrations of metals in sediments have been reported for numerous other water bodies (Forstner and Wittmann, 1983). Of more interest than the past increase in contaminants, however is the decrease now occurring in Puget Sound.

The lower recent contamination levels of Pb, Ag, and Hg should be of great significance to regulatory agencies if the decreases are indeed the result of reductions in the pollutant loading to Puget Sound. The past maximum concentrations suggest that Puget Sound was more contaminated 10-30 years ago, and that as the loading

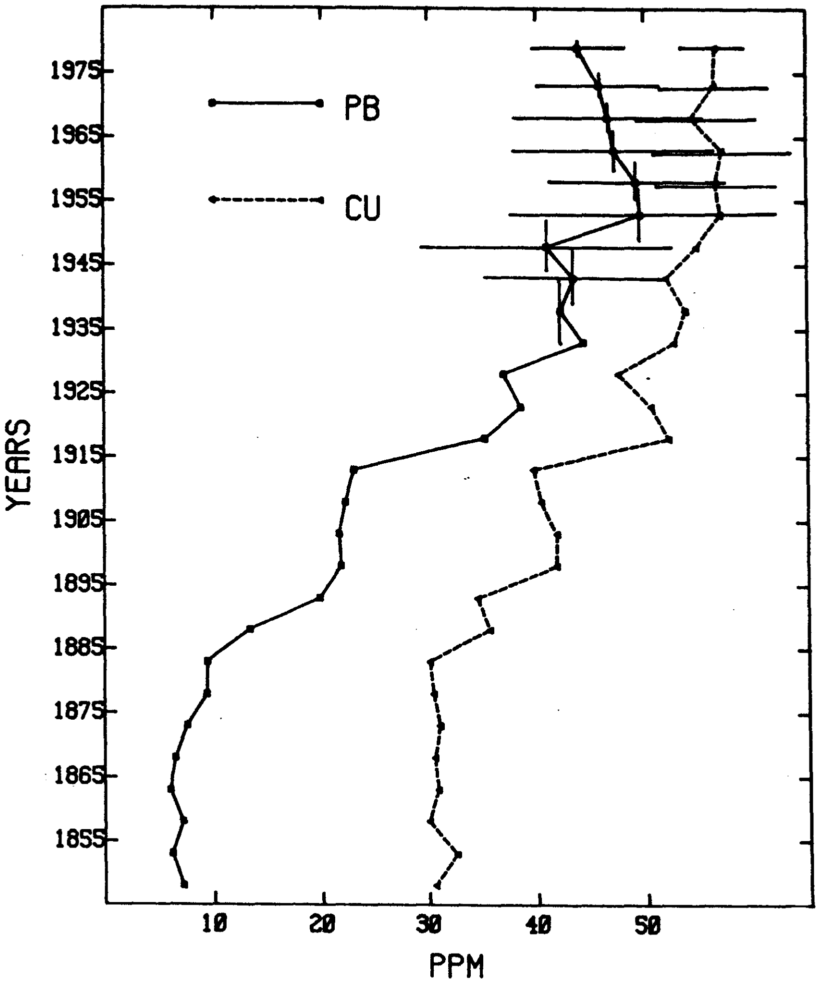

FIGURE 1. Profiles of Mean Concentrations of Pb and Cu in Nine Fine-Grain Sediment Cores as a Function of Sediment Age. Concentrations in $\mu g\ g^{-1}$ (ppm) Dry Wt. Horzontal Error Bars are the 95% Confidence Intervals for the Standard Error of Mean. The Vertical Error Bars are ± 1 s.d.

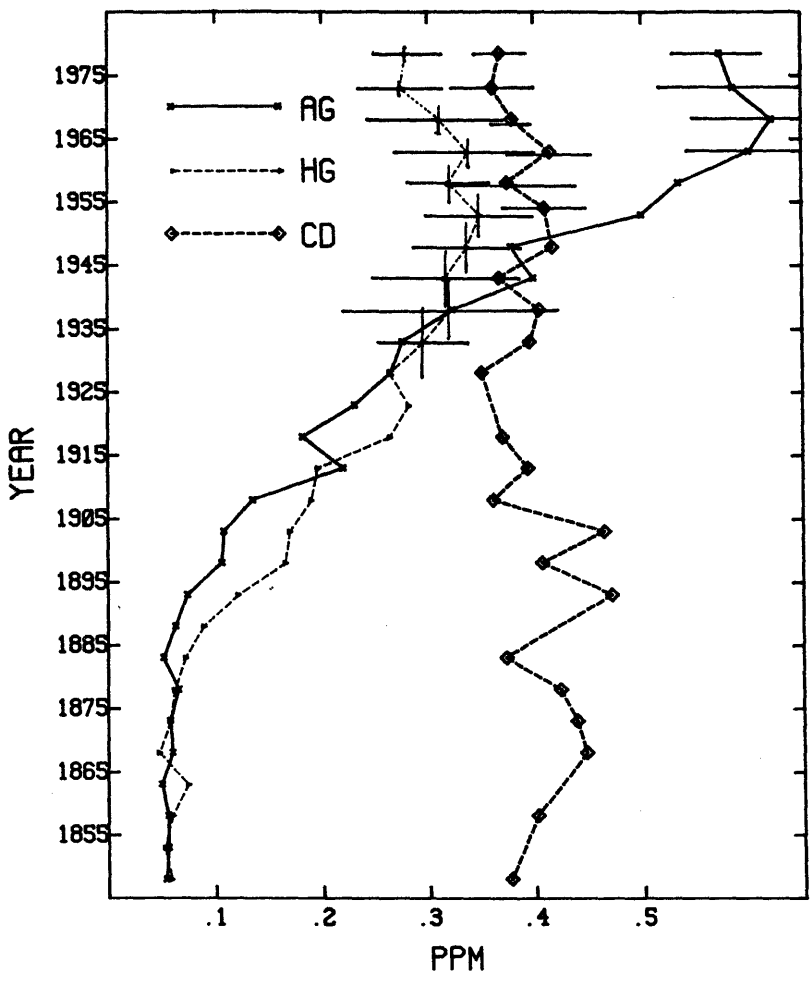

FIGURE 2. Profiles of Mean Concentrations of Ag, Hg, and Cd in Nine Fine-Grain Sediment Cores as a Function of Sediment Age. Concentrations in $\mu g \ g^{-1}$ (ppm) Dry Wt. Error Bars are 95% Confidence Intervals.

decreased during the last decade the sediment quality has improved. For the sediment quality to improve, cleaner sediment must be deposited on the older sediment. Also, the rate of sediment mixing must be slow relative to the sedimentation rate, or a small change in input rate could not be detected for many years. Evaluation of the sources of contaminants to Puget Sound indicates that rivers and shoreline erosion supply relatively clean sediments to the basin (Dexter et al., 1981; Curl, 1982; Crecelius et al., 1983).

Organic chemicals

The sedimentary history of hydrocarbons recorded in fine-grain sediments of the central basin shows increased concentrations paralleling the urbanization of the Seattle-Tacoma area. The maximum concentrations of polynuclear aromatic hydrocarbons (PAH), unresolved complex mixtures (UCM), and n-alkanes were found in sediments deposited in the 1940s (Fig. 3). Gschwend and Hites (1981) reported similar PAH maximum levels in sediment cores from Europe and the United States. Bates et al. (1984) suggest this maximum corresponds to the period when the maximum number of Seattle area dwellings used coal or wood for heating. More recently, dwellings have been heated with gas, electricity or oil, which produce relatively small amounts of combustion particles. Barrick (1982), and Barrick and Pral (1987) have estimated that sewage and atmospheric dust-fall are the major contributors of PAH to central Puget Sound. Although total anthropogenic (man-caused) pollution is probably still increasing, air pollution control devices to reduce particle emissions may be keeping atmospheric particulate PAH concentrations at a steady level.

The sedimentary histories of alkanes and UCM, show a similar increase with increased industrialization of the Seattle-Tacoma area (Fig.3) (Bates et al., 1984; Barrick et al., 1980). The maximum concentratons are found at approximately 1965, the time period when Seattle's largest sewage treatment plant (METRO) came on line. Prior to that time, much of Seattle's sewage was discharged untreated into Puget Sound. The decline in UCM and alkane concentrations in recent sediments may be attributable to METRO.

The temporal trends in the contaminations of central Puget Sound with synthetic organic chemicals, such as polychlorobiphenyl (PCB) and the pesticide DDT, are similar to the metals and hydrocarbons, except the appearance of these chemicals did not occur until about the 1930s (Fig. 4). These compounds show maximum subsurface levels in the 1950s and 1960s. The profiles of these chemicals generally follow the history of industrial production and release to the environment. The surface sediments of Puget Sound have been gradually recovering since the discharge of these chemicals to Puget Sound was virtually stopped.

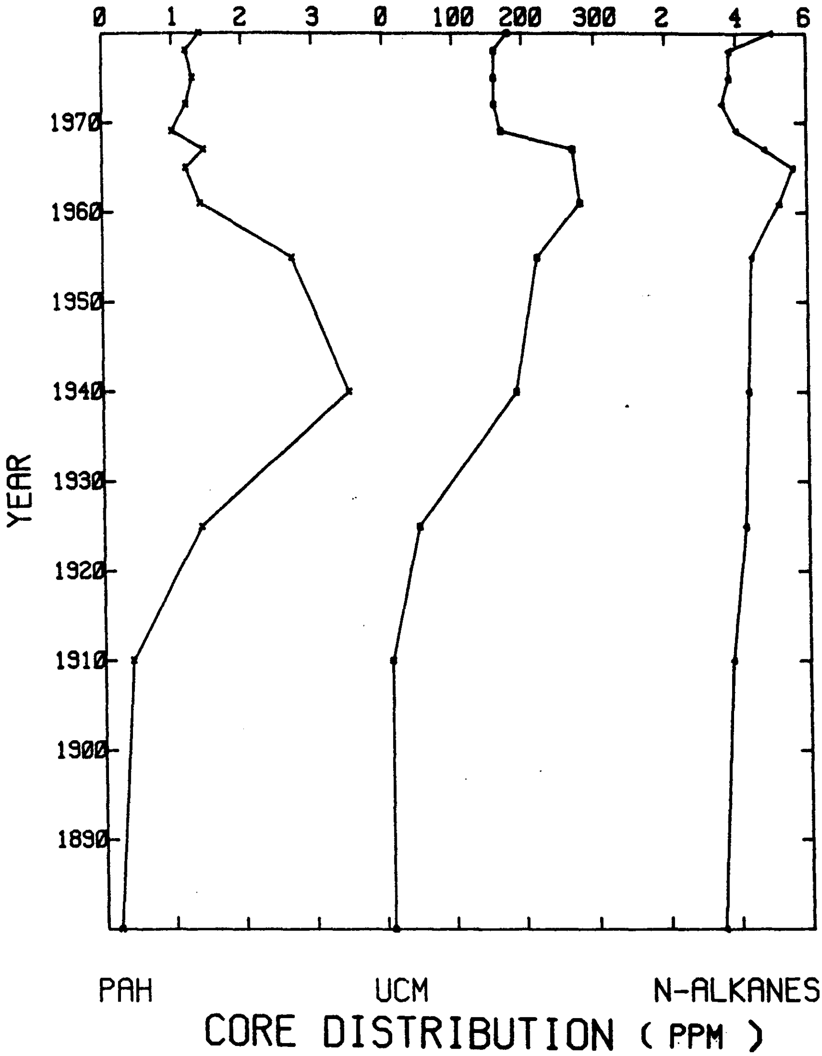

FIGURE 3. Profile of PAH, UCM and n-alkanes as a Function of Sediment Age. Concentrations in $\mu g\ g^{-1}$ (ppm) Dry Wt. Source of Data, Bates et al. (1984)

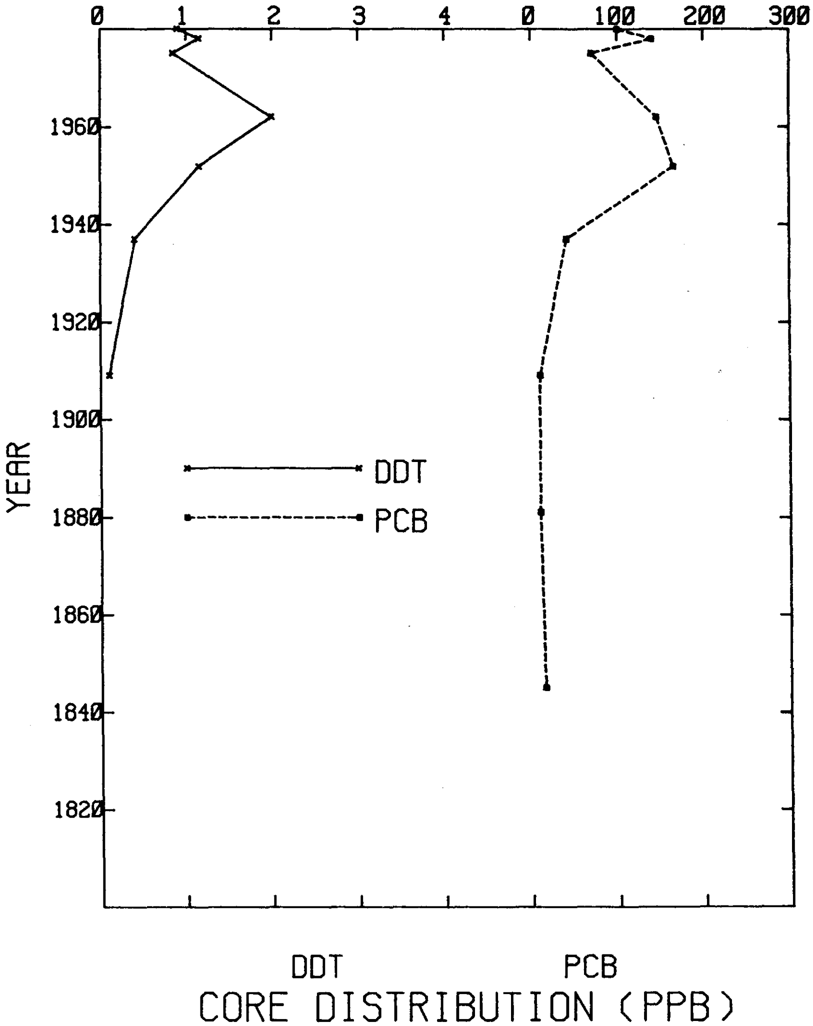

FIGURE 4. Profile of Mean Concentrations of DDT and PCB in Three Sediment Cores as a Function of Sediment Age. Concentrations in µg/Kg-1 (ppb) Dry Wt. Source of data, Romberg et al., (1984).

Recent Functions

As a result of source control, including restrictions on the use of materials for certain applications (e.g., lead in gasoline, PCBs in anything, DDT), pretreatment requirements (e.g., laundries and plating plants), economic trends (e.g., decreases in shipbuilding, the closure of smelters) and technological trends (e.g., the conversion of home heating from coal fuel to oil to electricity), it is apparent that source functions of both metallic and organic contaminants to Puget Sound, and other estuaries, should be and are decreasing.

The Seattle West Point Treatment Plant provides approximately half of the primary treated sewage to Puget Sound. Concentrations of Zn, Cu, Cr, and Pb have been decreasing in its effluent since at least 1980 (Romberg et al., 1987). Zn, Cu and Pb loadings decreased by 80% (Fig. 5). Since the sources for these metals are different and have changed at different rates, improved performance of the plant operations is probably the reason. In addition, Cu has shown a further decrease since 1982 when a water hardening program was instituted to preserve copper plumbing. Further reductions in all contaminant inputs from sewage effluent can be expected as plants throughout Puget Sound convert to secondary treatment. However, these gains will be offset somewhat as the Puget Sound watershed population continues to grow. The Puget Sound Council of Governments (PSCOG) (personal communication) estimates that populations in the four urban counties, King, Pierce, Snohomish and Kitsap will increase by 20%, to over three million people by the year 2000. Since at least METRO is beginning to produce effluent closer to secondary treatment as regards to trace metals and toxic organics, it would appear that inputs of these substances will remain close to steady state for the foreseeable future.

As alluded to earlier, most major pollutant point source functions are declining. However, as yet uncontrolled combined sewer overflows, non-point runoff and some industrial sources remain, and are very difficult to monitor. For example, in 1986 surface plumes enriched in dissolved trace metals were found off Harbor Island in Elliot Bay, an industrial area with many shipyards, and off the Denny Way CSO (Curl et al., 1987). Dissolved Cu concentrations exceeded the EPA criterion by 2.5 times off Harbor Island; other metals were in high concentration, but lower than the criteria. Off the Denny Way CSO, Cu concentrations exceeded the criterion by 3 times.

Finally, "hot-spots" remain as potential source areas but without further additions, are gradually being buried by sediments.

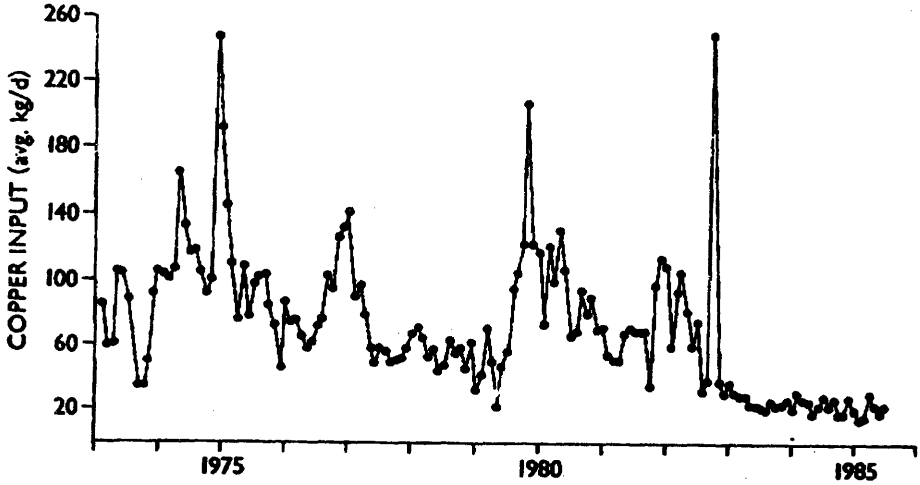

FIGURE 5. Monthly Averages of Copper Loadings in West Point Sewage Treatment Plant Effluent (1973-1985) in Kilograms per Day. A Downward Trend Since 1975 Apparently has Resulted From Improved Plant Operation and Source Control. The Low Levels Achieved After 1983 are a Result of the Instituion of a Water-Hardening Program which Decreases Copper Pipe Corrosion.

Conclusions

The temporal trends of contamination of central Puget Sound, inferred from the chemical composition of age-dated sediment cores, indicate heavy metal and hydrocarbon contamination began in the late 1800s, reached a maximum in the mid-1900s and has begun to decrease in the last decade. Synthetic organics first appear in sediments deposited in the 1930s and reach a maximum in the 1950s.

Because of the relatively rapid flushing rate and rapid sedimentation rate in Puget Soud, changes in contaminant loading will result in relatively rapid changes in surficial sediment quality.

Acknowledgments

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Water Quality Trends in Puget Sound

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Introduction

The purpose of this study is to assess historical changes in water quality in Puget Sound (Tetra Tech, Inc., 1988). Growth of population and industry have caused increasingly large quantities of nutrients and other wastes to be introduced into the sound (National Oceanic and Atmospheric Administration, 1985; Puget Sound Water Quality Authority, 1986). The major focus of this project is to determine whether changes in nutrient concentrations and the intensities of algal blooms have occurred. Pollutants from pulp mills and sewage discharges are also investigated. Although toxic contaminants are an important concern in Puget Sound, they are not included in this study because of the lack of high quality, long-term data.

Previous studies of nutrients and algal blooms in Puget Sound contain little evidence that anthropogenic influences have changed nutrient concentrations or algal bloom intensities in the main basin of the sound [e.g., Duxbury, 1975; Municipality of Metropolitan Seattle (Metro), 1977]. However, relevant information is lacking from most regions of the sound, including the poorly flushed embayments (Jones and Stokes, Inc., 1984). Moreover, recent field and modeling studies of Budd Inlet suggest that anthropogenic nutrient enrichment may be enhancing the intensities of algal blooms in Budd Inlet by 30-50 percent (URS, Inc., 1986).

Methods

Data for this study were obtained from historical and ongoing monitoring programs of the University of Washington Department of

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Oceanography, Washington Department of Ecology, Washington Department of Fisheries, and Metro. Before the data were used, the validity of the field and laboratory techniques used to produce the data was confirmed. Also, computer files containing the data were examined for completeness and corrected for inconsistencies in data coding and units of measurement.

Thirteen study areas were investigated (Figure 1). Data were combined from two or more sources to obtain the longest possible period of data coverage for each study area. Data collection began during the 1950s at 11 of the study areas and during the 1930s at 2 of the study areas. Data from all the sites were available through 1986.

Long-term and recent temporal trends were analyzed statistically. Because the study focused on algal blooms, the analyses were limited to the portion of the year when algal blooms occurred in each study area. Long-term trends were defined as changes in water quality that occurred over the entire period for which data were available (i.e., usually 1950s-1986). Recent trends were defined as changes in water quality that occurred since 1973. Thus, the recent data are a subset of the long-term data.

Results

Physical conditions

Salinity values decreased in eight study areas, while water temperature values increased in seven study areas. For example, at 10-m depth since the 1950s, declines in salinity values ranged from 0.4 to 1.5 ppt, and increases in water temperature values ranged from 0.5 to 1.4^{o} C. The water temperature increases are consistent with the observed warming of the climate in the Seattle area (i.e., mean annual air temperature has increased approximately 1.1^{o} C since 1945). However, the salinity decreases are not consistent with the observed decline in rainfall in the Seattle area (i.e., total annual rainfall has declined approximately 20 percent since 1945). A possible explanation for the salinity decreases is decreased inputs of oceanic water from the Strait of Juan de Fuca, but this hypothesis could not be tested during this project.

Dissolved oxygen

Dissolved oxygen concentrations increased in seven study areas located in southern Puget Sound or Hood Canal. At 10 m depth, these increases ranged from 0.7 to 1.7 mg/L since the 1950s. The sites in southern Puget Sound were influenced by unusually high dissolved oxygen concentrations (up to 15 mg/L) at depths of 0 to 30 m in 1986. The cause of these high dissolved oxygen concentrations is not known. Because the maximum values were observed during different months in the affected areas, a single, particularly intense, algal bloom probably could not be the cause.

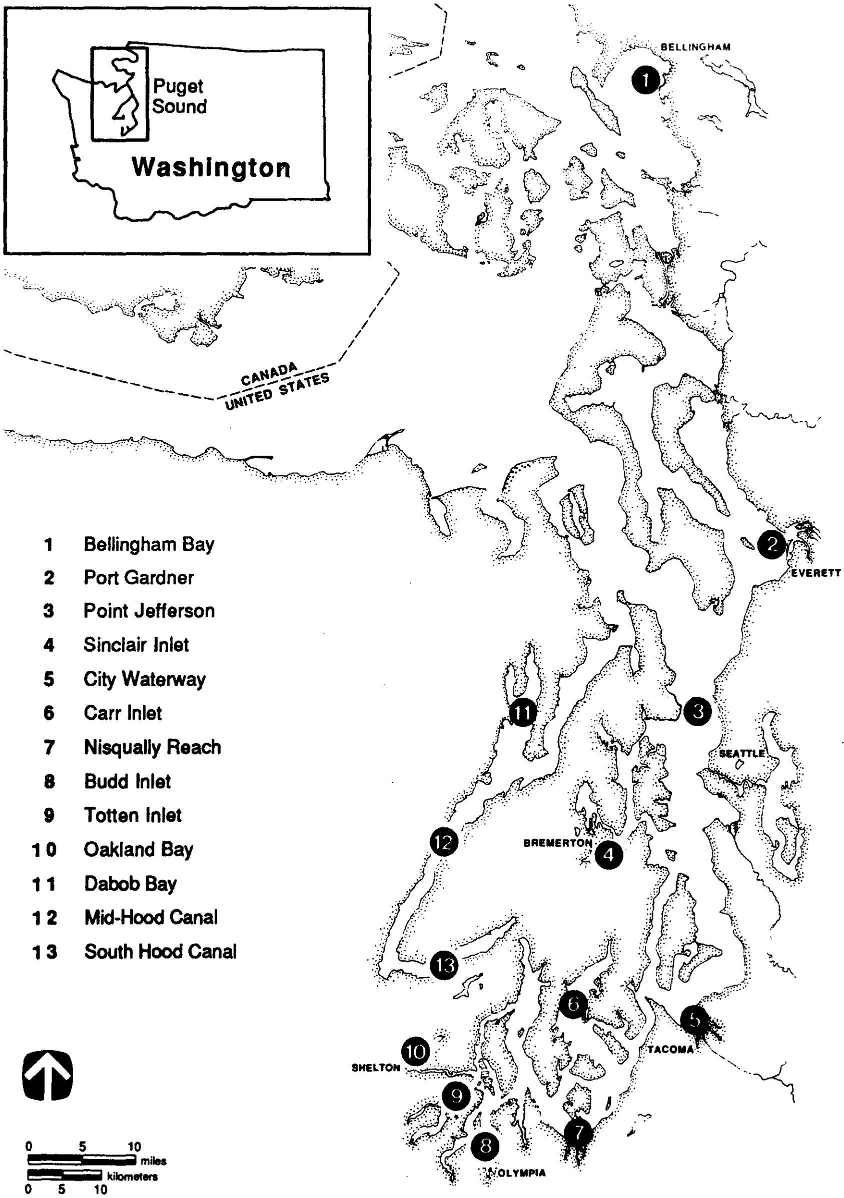

Figure 1. Study area locations.

Unusually high dissolved oxygen concentrations were not observed in Hood Canal in 1986, and the increases in dissolved oxygen concentrations detected in Hood Canal occurred gradually.

With the exception of the Oakland Bay study area, very low dissolved oxygen concentrations (e.g., <3 mg/L) were rarely observed. The lowest mean dissolved oxygen concentration (4.3 mg/L) was observed at 30-m depth in the South Hood Canal study area. At the Oakland Bay study area, sulfite waste liquor discharged from the pulp mill in the City of Shelton reduced dissolved oxygen concentrations, occasionally down to zero. After the mill closed in 1957, very low values were not observed in Oakland Bay.

Nutrients

Nitrate data are available only since the mid-1970s. Substantial decreases in nitrate concentrations were detected in the Carr Inlet and South Hood Canal study areas. For example, decreases since 1976 averaged approximately 6 ug-at/L at 30-m depth. The changes were increasingly erratic and smaller in magnitude along a south to north gradient in Hood Canal. Therefore, the factor affecting nitrate concentrations in Hood Canal [apparently algal blooms (see below)] was probably most influential in southern Hood Canal.

Long-term (1950s-1986) decreases in phosphate concentrations were detected in seven of the nine study areas for which long-term phosphate data are available. These decreases ranged from 0.2 to 0.8 ug-at/L at 10-m depth. Thus, phosphate concentrations were higher in most areas during the 1950s than during the mid-1980s. The cause of these declines is not known, but because decreases were detected in both rural and urban sites, anthropogenic influences do not appear to explain these results.

Recent (1973-1986) increases in phosphate concentrations were detected in 6 of the 12 study areas for which recent data are available. The increases ranged from 0.6 to 1.0 ug-at/L at 10-m depth. However, in the sites where data are available from the 1950s, the recent increases did not bring concentrations up to levels observed during the 1950s. All the recent increases occurred in urban study areas, while no statistically significant recent changes ($P>0.3$) were detected in rural study areas (Figure 2). Thus, phosphate concentrations have increased since the mid-1970s in urban areas, but have not changed in rural areas. These results suggest that the recent increases in phosphate concentrations may be attributed to anthropogenic factors.

Phytoplankton abundance

Few trends were detected in the values of variables used as indicators of phytoplankton abundance (chlorophyll *a* concentration, percent dissolved oxygen saturation in surface water, Secchi disk depth). However, based primarily on oxygen saturation data,

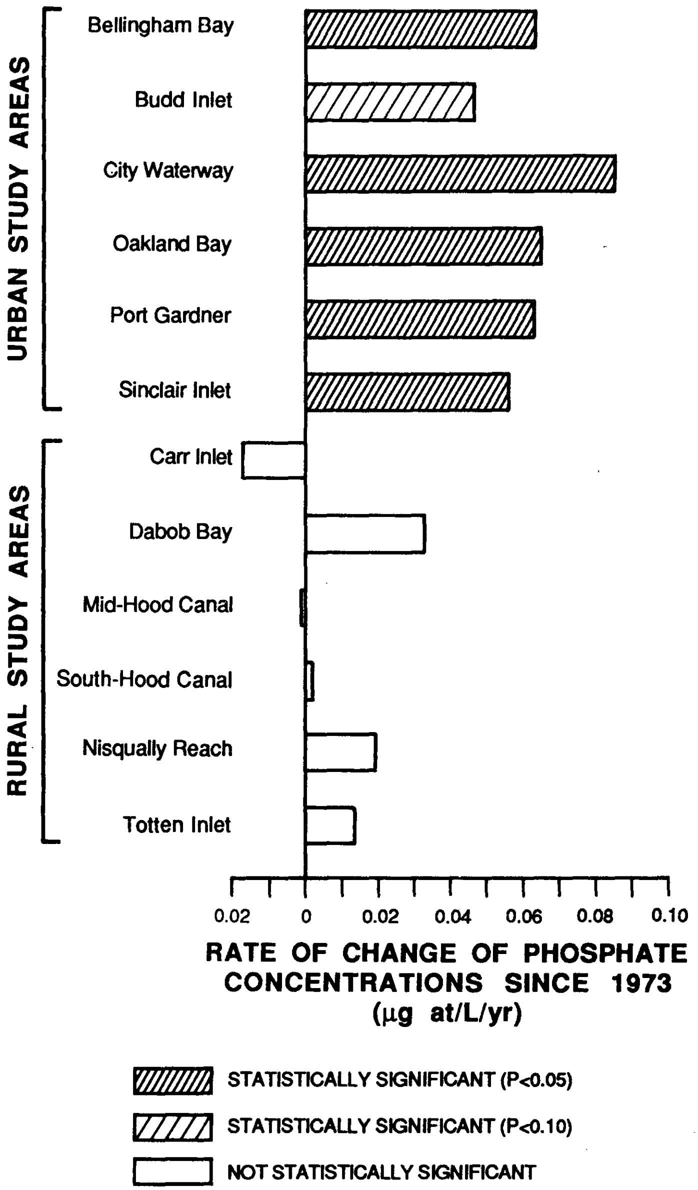

Figure 2. Rates of change of phosphate concentrations since 1973 in urban and rural study areas.

phytoplankton abundance appears to have increased in the study areas in Carr Inlet and Hood Canal. In the Carr Inlet study area, percent dissolved oxygen saturation at the surface has increased by approximately 30 percent and Secchi disk depth has decreased by approximately 50 percent since 1977. However, the values of both of these variables fluctuated erratically over this time period. In Hood Canal, the phytoplankton increases appear to have occurred in relatively deep water (i.e., 10-m depth). Changes in dissolved oxygen saturation at the surface and Secchi disk depth were not statistically significant. However, water transparency is high in Hood Canal (i.e., mean Secchi disk depths ranged from 4.8 to 6.0 m in the three study areas on Hood Canal), and increases in percent dissolved oxygen saturation at 10-m depth probably can be attributed to increased photosynthesis near this depth. The increases in percent dissolved oxygen saturation at 10-m depth ranged from 20 to 30 percent, with the largest increase occurring at the South Hood Canal site and the smallest increase occurring at the Dabob Bay site.

Pollutants

Concentrations of sulfite waste liquor (measured by the Pearl Benson Index) were analyzed as an index of pollutants from pulp mills. Sulfite waste liquor concentrations declined in all four study areas located near pulp mills: Bellingham Bay, Port Gardner, Commencement Bay, and Oakland Bay. Since the mid-1950s, 10-fold decreases were detected in the Bellingham Bay, Port Gardner, and Oakland Bay study areas. A decrease of approximately 50 percent was detected in the Commencement Bay study area. [The pulp mill on Commencement Bay is a kraft mill, and does not discharge sulfite waste liquor. However, the wastes discharged by the mill are detected by the Pearl Benson test (Henry, C., 17 November 1987, personal communication).]

Declines in sulfite waste liquor concentration generally coincided with improvements in the waste treatment processes used by local pulp mills, although the decline at the Oakland Bay study area occurred when the nearby pulp mill closed in 1957. Concentrations of sulfite waste liquor at the Port Gardner study area are plotted by year in Figure 3. In Port Gardner, sulfite waste liquor concentrations dropped after the local pulp mill adopted secondary effluent treatment in 1980.

Decreases in concentrations of fecal coliform bacteria in some areas appear to be attributable to changes in point sources. For example, the mean fecal coliform bacteria concentration in the Bellingham Bay study area declined from approximately 6 organisms/100 mL in 1974 to <1 organism/100 mL in 1986. The decreases coincided with improvements in sewage treatment facilities and elimination of combined sewer overflows in the City of Bellingham.

An apparent 25-fold increase in the concentrations of fecal coliform bacteria in the Port Gardner study area coincided with

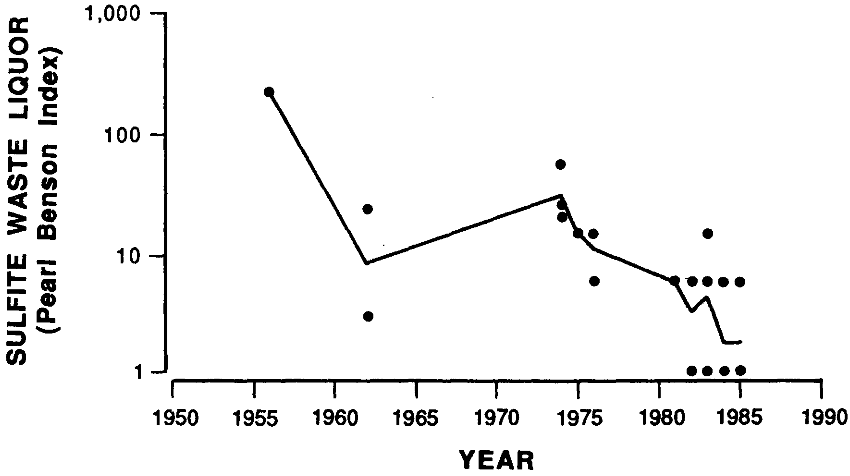

Figure 3. Concentrations of sulfite waste liquor near Port Gardner from 1956 through 1985.

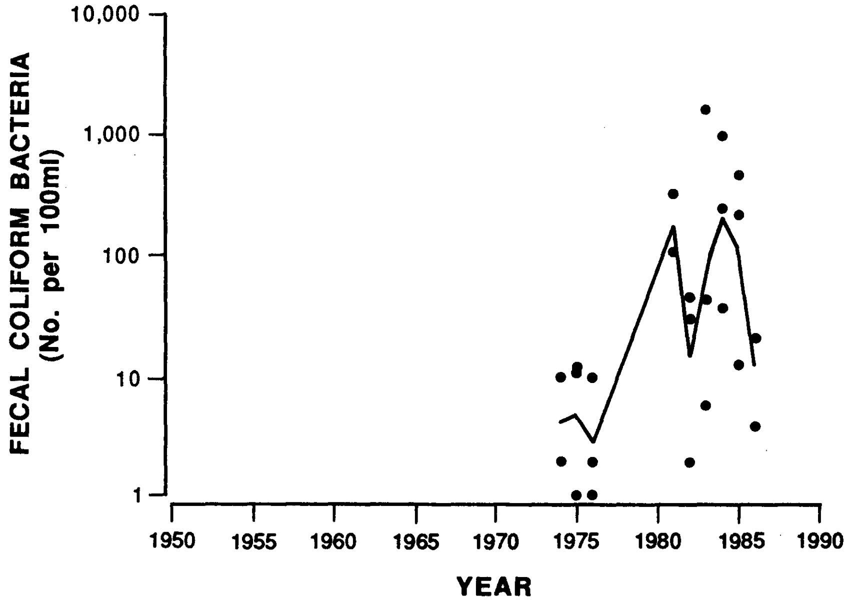

Figure 4. Concentrations of fecal coliform bacteria near Port Gardner from 1974 through 1986.

the onset of secondary effluent treatment by a local pulp mill in 1980 (Figure 4). This increase was probably due to discharges of the bacterium, Klebsiella, an organism that is detected in the standard fecal coliform tests, and that grows rapidly in the secondary treatment ponds of sulfite pulp mills.

Discussion

Numerous changes in water quality were detected despite the limited availability of high quality, long-term monitoring data. However, because the amount of data was limited, the results should not be considered definitive. The absence of detectable changes in a study area may indicate that no changes occurred, or that the available data did not provide sufficient resolution to detect changes that occurred.

Changes in salinity and water temperature values detected during this study highlight the importance of physical processes that affect water quality. For example, a change in salinity values in an area indicates that a change has occurred in the ratio between fresh and salt water. Because the concentrations of many chemicals are quite different in fresh and salt water, changes in salinity values provide information about the influence of changes in water sources on water quality. Also, the ability to interpret the water chemistry data in this study would have been enhanced if measurements of inputs from deep, oceanic water and from upland sources had been available.

Three factors may have contributed to the lack of observations of low dissolved oxygen concentrations in this study. Due to the lack of data, most study areas were not located in areas where this problem is most likely to occur (i.e., the heads of poorly flushed inlets). Also, the data generally do not include samples from bottom water, which typically is the depth at which dissolved oxygen concentrations are lowest within a site. Finally, the analyses included only the algal bloom period, while lowest dissolved oxygen concentrations typically occur after algal blooms (i.e., late summer, rather than late spring and early summer).

The cause of the long-term decline in phosphate concentrations, and the recent increases in phosphate concentrations in urban study areas, could not be determined. One possible explanation for the long-term decreases involves decreased inputs of phosphate in the oceanic water that enters Puget Sound from the Strait of Juan de Fuca, but this hypothesis could not be tested in this study. The recent increases in phosphate concentrations in the Bellingham Bay, Port Gardner, and Commencement Bay study areas may have been influenced by improvements in effluent treatment procedures used in nearby pulp mills [sulfite waste liquor removes phosphate from seawater solution (Westley and Tarr, 1978)]. However, other anthropogenic factors (e.g., increases in sewage discharges or runoff from fertilized areas) may have affected phosphate concentrations in all the urban study areas.

Probable changes in phytoplankton abundance were detected only in the study areas in Carr Inlet and Hood Canal. However, the lack of detectable changes in phytoplankton abundance may be attributed in part to inadequacies in the database. Systematically collected data on cell density, chlorophyll a concentrations, or photosynthesis rates would have provided direct measures of phytoplankton, but few such data were available. Some of the phytoplankton indicator variables used in this study are affected by variation in environmental factors other than phytoplankton (e.g., Secchi disk depth is reduced by suspended sediments in the water).

Recommendations

This project provided a unique opportunity to assess historical and existing monitoring programs by using the data in a water quality trends analysis. Recommendations derived from the experience of using the data and from the results of the study follow.

- One organization should oversee all water quality monitoring programs to facilitate compatibility of field and laboratory techniques and database formats, and to coordinate geographic coverage. U.S. Environmental Protection Agency's (U.S. EPA) Puget Sound Estuary Program has published a series of recommended protocols (U.S. EPA, 1986) to facilitate standardization of techniques used by researchers in Puget Sound.

- Changes in field and laboratory techniques should be documented; new techniques should be calibrated with old techniques.

- Goals of the monitoring program should be determined quantitatively before the study design is chosen (e.g., how much change in dissolved oxygen concentrations should be detectable over a given time period?). The efficacy of alternative study designs in detecting temporal trends should be evaluated with statistical power analysis using existing data.

- The influence of physical factors (e.g., climate, flows of oceanic and fresh water) on water quality should be monitored to improve understanding of ecosystem function and to enable comparison of the impacts of physical and anthropogenic factors on water quality.

- Water quality in Budd Inlet should be monitored to determine whether nitrogen removal by the LOTT sewage treatment plant reduces the intensity of algal blooms.

- A microbiological test is needed to distinguish between bacterial contamination from sewage and secondary effluents

from sulfite pulp mills (which contain the bacterium, Klebsiella). Because current fecal coliform bacteria tests cannot make this distinction, shellfish beds may be closed because of exposure to pulp mill effluent rather than exposure to sewage. Although not well studied in Puget Sound, the health risk from Klebsiella contamination appears to be less than the health risk from sewage contamination.

Acknowledgements

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Toxic Problems in Nonurban Areas of Puget Sound

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Introduction

The objective of this study is to assess, by interpreting existing information, possible contamination problems in nonurban areas of Puget Sound. The project currently is in progress, so final conclusions are not available. Therefore, examples are presented to illustrate the assessment process. Site rankings developed for this project will be used to help prioritize nonurban areas for possible detailed literature and field studies in the future. These studies would assess quantitatively the extent of problems in selected, high ranking areas. Evaluation criteria include historic and present sources of toxic chemicals, sediment condition, and biological impacts. Other environmental problems, such as paralytic shellfish poisoning and low dissolved oxygen concentrations, may also be important concerns in Puget Sound, but are beyond the scope of this study.

This study is an extension of the Urban Bay Action Program developed by U.S. Environmental Protection Agency's (EPA's) Puget Sound Estuary Program (PSEP) (U.S. EPA 1986). Under this program, abatement and remedial action strategies are developed and implemented for urban embayments contaminated by toxic chemicals within Puget Sound. Toxic chemicals may damage biological communities and enter the food chain, creating potential human health impacts.

Methods

The information in the study is grouped geographically into the 12 regions of Puget Sound used in the Puget Sound Environmental Atlas (Figure 1) (Evans-Hamilton, Inc. and D.R. Systems, Inc. 1987). The following seven urban areas are excluded from the study: Bellingham Bay, Everett Harbor, Eagle Harbor, Elliott Bay, Sinclair Inlet, Commencement Bay, and Budd Inlet (Figure 1). These bays are not

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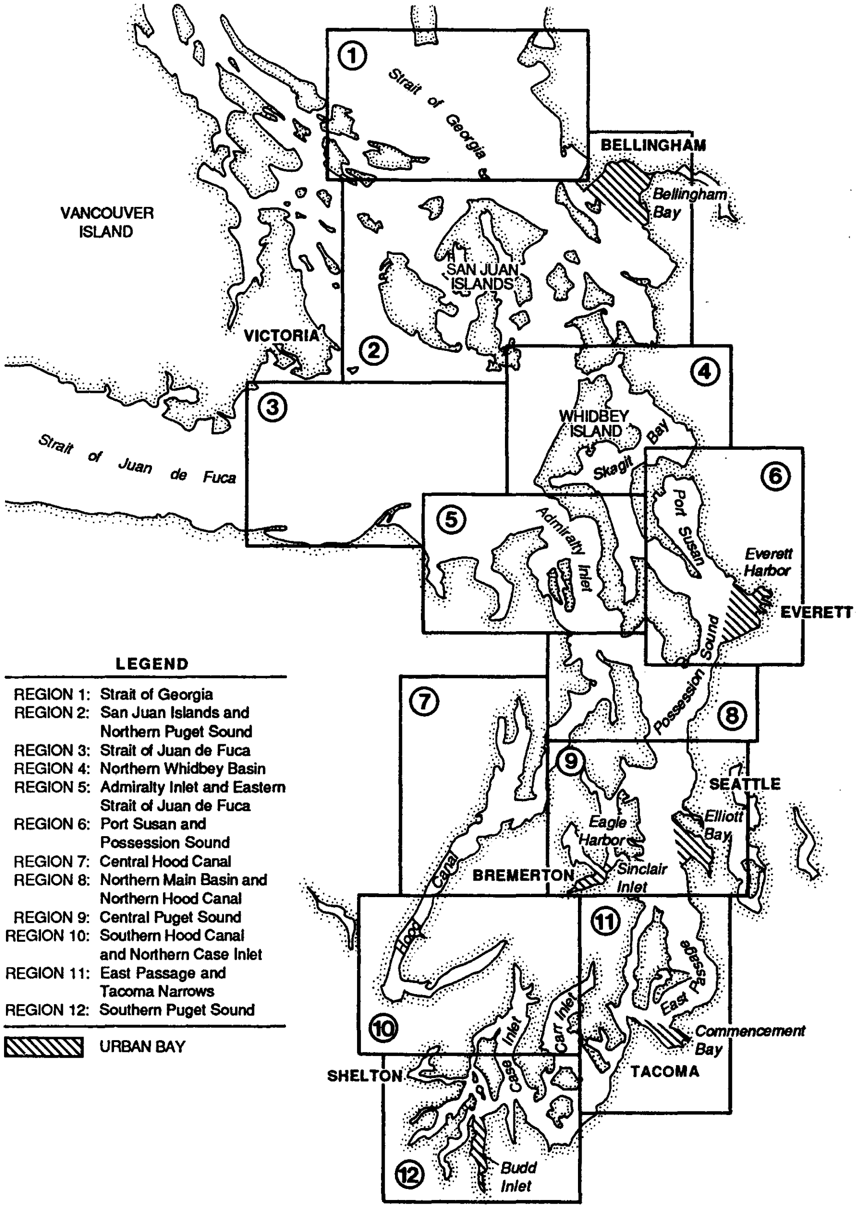

Figure 1. Regions of Puget Sound.

included because toxic contaminants are known to exist there and detailed studies are under way or being prepared for them.

Three categories of information are included in this report: sources of toxic substances (e.g., permitted discharges, hazardous waste generators, hazardous waste sites), sediment condition (i.e., concentrations of toxic contaminants in sediments), and biological impacts (i.e., sediment toxicity, altered benthic communities, bioaccumulation, histopathology of bottom fishes, and fish kills). These categories are consistent with those used in PSEP's Urban Bay Action Program (U.S. EPA 1986) for assessment of environmental degradation in the urban bays of Puget Sound.

The sources of information used in this project include scientific papers; government reports from the United States and Canada, Washington state, and local agencies; unpublished federal and state agency files; and reports produced by the private sector. Additional information was obtained during interviews with environmental professionals familiar with Puget Sound.

Assessment matrices

For each site included in this study, data on sources of toxic substances, sediment condition, and biological impacts will be incorporated into an assessment matrix for the region of the sound where the site is located. This information also will be combined for an overall evaluation of each site. Data for each of the above categories are evaluated for 1) level of concern (LOC) and 2) degree of certainty (DOC) for the assessment matrices. Ratings of low, medium, and high are assigned separately for each data category based on the severity of the potential problem (LOC), and on the amount and appropriateness of the available information (DOC). Details of the criteria used to determine the ratings will be available in a report by Tetra Tech, Inc. (1988).

Results

Examples of the assessments in this study are presented for two sites located in Region 8: Richmond Beach and Point Jefferson/President's Point. The results are preliminary assessments of problems that could exist in these two areas, but do not indicate that problems definitely exist.

Richmond Beach

Overall rating. The overall LOC rating is high; the overall DOC rating is medium.

Sources of toxic substances. The LOC and DOC ratings for sources of toxic substances are both medium. Approximately 2,400 kg of hazardous wastes were generated by the petroleum industry in the

area during 1984 (Washington Department of Ecology 1984). There is a small sewage outfall (<2 MGD) in the area (Tetra Tech, Inc. 1984).

Sediment condition. The LOC rating for sediment condition is high; the DOC rating is medium. Six stations near the Richmond Beach Sewage Treatment Plant outfall were sampled during 1981-1982 in the Municipality of Metropolitan Seattle (Metro) Toxicant Pretreatment Planning Study (Metro 1984). At two stations, one organic compound (N-nitrosodiphenylamine) was found in concentrations well above the Apparent Effects Threshold (AET) [i.e., the concentration at which biological impacts have always been detected in Puget Sound (Tetra Tech, Inc. 1986)]. In addition, concentrations of five other organic compounds and one metal (zinc) exceeded concentrations found in reference areas by >10 times, but these concentrations did not exceed AET values.

Biological impacts. The LOC and DOC ratings for biological impacts are high. In 1984, approximately 29 percent of a sample of 21 English sole (*Parophrys vetulus*) was found to have liver lesions (Krahn et al. 1986). An unknown pollutant caused a fish kill of juvenile salmonids in 1985 (LeVander, L., 3 March 1987, personal communication). One organic compound (di-n-butyl phthalate) has been detected in crab muscle tissue (*Cancer* spp.) at concentrations >5 times higher than the detected concentrations in reference areas (Metro 1984). Bioassay data are not available.

Point Jefferson/President's Point

Overall rating. The overall LOC rating is medium; the overall DOC rating is low.

Sources of toxic substances. No information is available.

Sediment condition. The LOC rating for sediment condition is medium; the DOC rating is low. Two stations have been sampled near Point Jefferson (Metro 1984). The concentrations of two metals and two organic compounds exceeded reference concentrations by >10 times, but no concentrations were in excess of AET values.

Biological impacts. The LOC and DOC ratings for biological impacts are medium. In 1984, 20 percent of a sample of 20 English sole (*Parophrys vetulus*) was found to have liver lesions (Krahn et al. 1986). However, Malins et al. (1987) reported no incidences of liver neoplasms or pre-neoplasms in a sample of 40 English sole. The available bioaccumulation data do not indicate that substantial elevations of tissue contaminants occur in the area (Malins, D.C., 22 July 1985, personal communication; Krahn et al. 1986). Bioassay and fish kill data are not available.

Discussion

The approach in this study can be used to compile and interpret scarce data for a large geographical area. This approach is necessary in defining environmental problems in the less developed and less studied areas of Puget Sound. The first step in this approach is to screen available information, with the objective of determining where environmental problems might exist outside the urban bays of Puget Sound. Steps to be followed in the future include detailed literature studies and field investigations of areas that emerge from this study as high priority sites. The purpose of future studies would be to obtain a more comprehensive and current data set to assess problems and develop remedial actions for nonurban areas of Puget Sound.

Acknowledgements

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Decade-Long Regimes of a Fjord Basin's Oceanography, Hydrology, and Climatology: Puget Sound, 1916-'87

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Abstract

Data collected at eleven sites in the Pacific Northwest during 1916-'87 indicate that the flow pattern in Puget Sound's Main Basin oscillates between two regimes (I, II) each typically lasting a decade and having distinct oceanographic, hydrologic, and climatic characteristics.

Introduction

Long records of environmental measurements often contain fluctuations over time intervals spanning several years to decades. This paper shows that the currents measured in Puget Sound's Main Basin co-oscillate with conditions on the Pacific Coast and in the Cascade Mountains (Fig. 1). These conditions were grouped into two regimes shown schematically in Figure 2. Supporting analyses, physical explanations, and references will appear in a longer paper to be published by the American Geophysical Union. Figures appear at the end of the paper.

Data

Oceanographic, hydrologic, and climatic measurements made in the Pacific Northwest U.S. were examined for evidence of prominent regimes (Fig. 1).

<u>Site 1: Coastal Conditions</u> - Departures of annual average sea level and sea surface temperature from long-term means were computed for the Pacific Coast from monthly data at Neah Bay.

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Sites 2, 3: Source Water Conditions - Annual average temperature and salinity of the oceanic water flowing inland near the bottom of the Strait of Juan de Fuca were computed from monthly observations made at Pillar Point at 140 m (Site 2). Characteristics of the source water farther inland (Site 3) were also compared with the Basin's properties.

Sites 4, 5: Runoff - Monthly discharge from the two largest rivers influencing the Basin were averaged within calendar years (Site 4, Fraser River at Hope, British Columbia; Site 5, Skagit River at Concrete, Washington).

Sites 6, 7: Basin Water Properties - Temperature, salinity, and density were averaged within months and calendar years from observations made in the vicinity of sites 6 and 7 by the University of Washington and the Municipality of Metropolitan Seattle.

Sites, 8, 9: Currents - Current speed and direction were measured with Aanderaa current meters at sites 8 (1972-'81) and 9 (1983-'84). Fortnightly fluctuations were suppressed by averaging the observations over 28-day intervals.

Site 10: Wind - Hourly wind speed and direction at Tacoma were summarized by month from records of the Puget Sound Air Pollution Control Agency.

Site 11: Snow Depth - Depth of snow as measured on 15 March for each year was obtained for the Paradise Ranger Station located on the southern side of Mount Rainier.

Methods

Several methods were developed to reduce the number of variables necessary for description of the regimes.

1. Correlations amongst the current meter data showed that the depth of no-net-motion separating the upper and lower flow layers at Site 8 was nearly constant (~56 m). In the lower layer deeper than 56 m, observations near 100 m depth (hereafter the mid-depth speed U_m) were correlated with speeds at greater depth. When the mid-depth speed exceeded ~6 cm/s, the fastest inflow tended to be near 100 m; at slower mid-depth speeds the fastest inflow deepened (Fig. 3).

2. Annual averages of temperature, salinity, and density made at a single depth were found to be representative of other depths in the lower layer.

3. To obtain a time series giving approximately equal weight to observations representative of the coast, Basin, and mountains a

dimensionless departure (δ) of annual averages from historical mean values was formulated using three highly correlated variables,

$$\delta = \frac{1}{3}\left(\frac{\Delta T_c}{\sigma_{\Delta T_c}} + \frac{T_b - \overline{T_b}}{\sigma_{T_b}} + \frac{\overline{SD} - SD}{\sigma_{SD}}\right) , \qquad (1)$$

where: σ, standard deviation of subscripted variables; overbars, mean values over the record length; ΔT_c, coastal sea-surface temperature anomaly; T_b, Basin temperature; and SD, snow depth. Negative δ were defined as Regime I and positive values as Regime II.

Characteristics of the Regimes

Correlations amongst the eleven sites resulted in a schematic diagram for conditions during the Regimes (Fig. 2).

1. Duration and strength - The dimensionless departure (δ ; eq. 1) was computed from annual averages between 1916-'87 and smoothed using a 5-year running, equally weighted average (Fig. 4). Statistical analyses yielded the following characteristics of the smoothed departure: the mean (standard deviation) of the duration between zero crossings equalled 8.9 (2.3) years; maximum departures during each regime averaged 0.7 standard deviations from the long-term mean.

2. Basin conditions - The smoothed departure was highly correlated with the mid-depth current speed (correlation coefficient, $r = +0.86$; Fig. 5). Given the other correlations between the mid-depth speed and flow patterns in the lower layer, the Basin's current structure corresponding with the Regimes varies approximately as illustrated in Figure 3. This result together with the departures shows that: Regime I, fastest inflow occurs near mid-depth when the Basin is relatively cold ($< 9.7^{\circ}C$); Regime II, fastest inflow occurs toward bottom when the Basin is relatively warm ($> 9.7^{\circ}C$).

3. Coastal conditions - The correlations with coastal temperatures indicate that during Regime I sea level stands below normal and that colder, more saline water flows toward Puget Sound along the bottom of the Strait of Juan de Fuca. Conversely, during Regime II sea level stands above normal and warmer, less saline water flows inland.

4. Mountain conditions - The correlations with snow depth indicate that during Regime I southerly winds during winter are more frequent and deposit a deeper than normal snowpack in the Cascade Mountains. Consequently runoff from higher elevation is also above normal. Conversely, during Regime II southerly winds, snowpack, and upper elevation runoff lie below normal.

Summary and Conclusions

1. Strong, decade-long regimes (I, II) account for a large fraction of the interannual variability of oceanographic, hydrologic, and climatic measurements made in Puget Sound and approaches.

2. The regimes may be characterized as follows (see Fig. 2):

   I. On the Pacific Coast colder, more saline water flows inland toward Puget Sound along the bottom of the Strait of Juan de Fuca while sea level lies below normal. At below normal temperature the fastest flow into the Main Basin occurs near mid-depth. Meanwhile more frequent southerly winter winds deposit a deeper than normal snowpack in the Cascade Mountains and as a result high elevation runoff lies above normal.

   II. On the coast warmer, less saline water flows toward Puget Sound and sea level lies above normal. At warmer temperatures the fastest inflow in the Basin occurs toward the bottom. Meanwhile winter winds are less frequent from the south; consequently snowpack and runoff fall below normal.

3. The mean (standard deviation) of the regimes' duration equals 8.9 (2.3) years. Since Regime II has persisted since 1977, we speculate that conditions in the Pacific Northwest should soon reverse to those of Regime I and remain so through most of the 1990's.

4. Because the time required to complete a cycle through two regimes (~2 decades) is comparable to the length of many environmental data sets available for Puget Sound, particularly marine biological and chemical observations, trends or means derived from short records should be viewed with caution.

Acknowledgments

We thank the many individuals who generously shared with us their thoughts, experience, and data: Mark D. Albright, University of Washington; Robert S. Barnes, Puget Sound Power and Light Company; Charles D. Boatman and Elizabeth A. Quinlan, URS Consultants; Janet F. Condon, Municipality of Metropolitan Seattle; Robert C. Hamilton, Evans-Hamilton, Inc.; K.B. Knechtel, Puget Sound Air Pollution Control Agency; Lee P. Krogh, National Weather Service (NOAA); Alan J. Mearns, Pacific Office Ocean Assessments Division, NOAA; James R. Holbrook, Harold O. Mofjeld and James E. Overland, Pacific Marine Environmental Laboratory, NOAA; and Wendell V. Tangborn, HyMet Company.

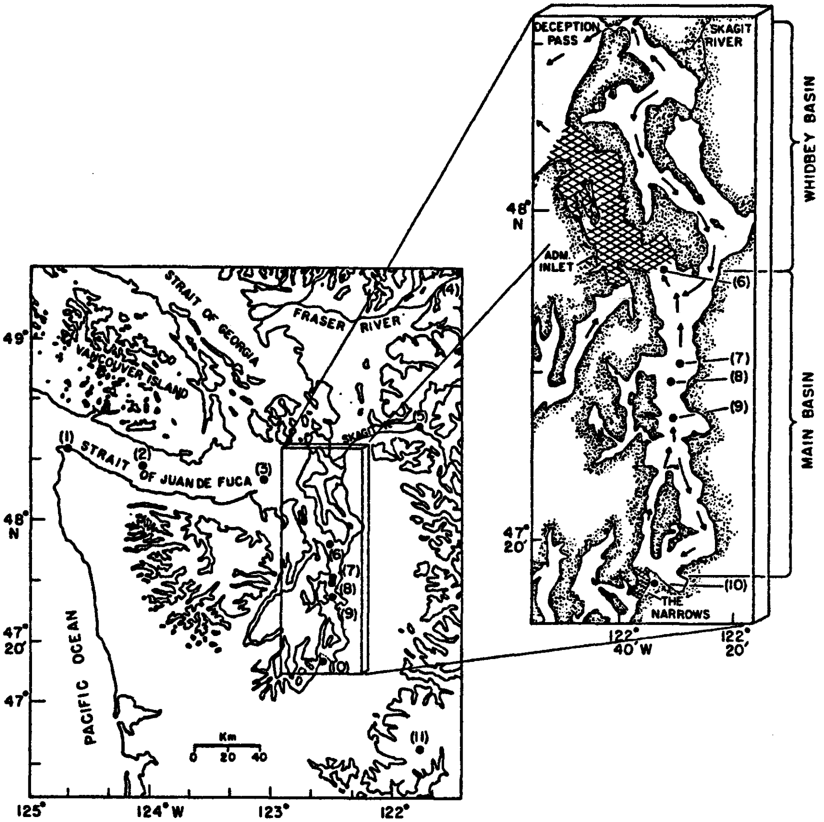

Fig. 1. Puget Sound's Main Basin (inset) and approaches showing sources of data (dots): Site (1), Neah Bay, sea surface temperature and sea level data; Site (2), north of Pillar Point, source water temperature and salinity data; Site (3), northeast of New Dungeness Spit, density data immediately seaward of Admiralty Inlet; Site (4), Hope, Fraser River discharge data; Site (5), Concrete, Skagit River discharge data; Site (6), Point No Point, Basin temperature and salinity data; Site (7), Point Jefferson, Basin temperature and salinity data; Site (8), off Meadow Point, current meter data; Site (9), off Elliott Bay, current meter data; Site (10), North 26th and Pearl Streets, wind data; and Site (11), Paradise Ranger Station, snow depth data. The 2500 foot contour for mountains is also shown. Notation for inset: hatched areas, sill zones; arrows, direction of surface flow carrying large fractions of freshwater; dots, data locations.

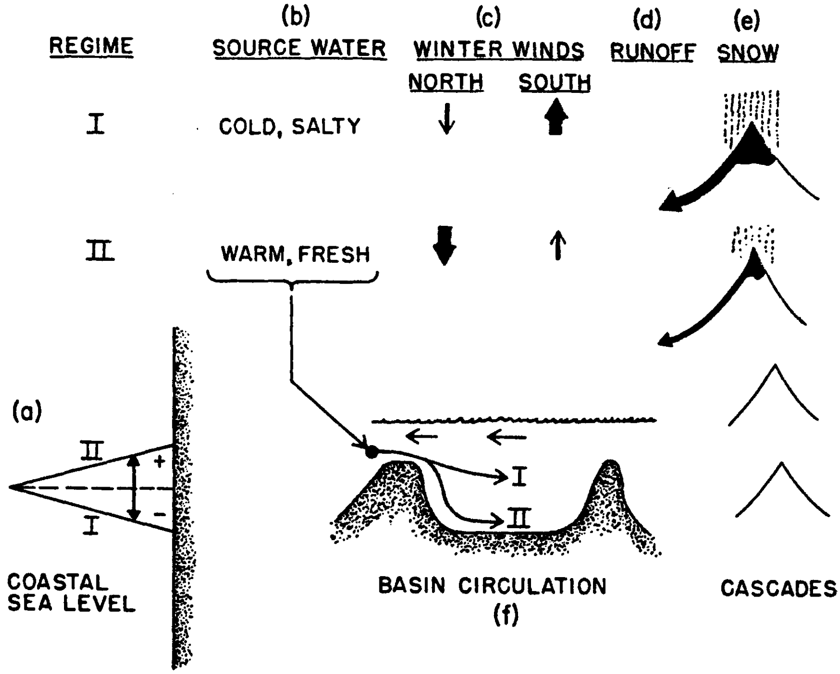

Fig. 2. Behavior of oceanographic, hydrologic, and climatic variables during two regimes (I, II): a) Pacific coast sea level; b) source water feeding inland to Puget Sound from the Strait of Juan de Fuca; c) winter winds over Puget Sound where arrow weight increases with frequency; d) runoff with discharge scaled by arrow weight; e) snow depth scaled by blackened area and density of snowfall; f) basin net circulation (arrows) with fastest inflow near mid-depth in Regime I and toward bottom in Regime II.

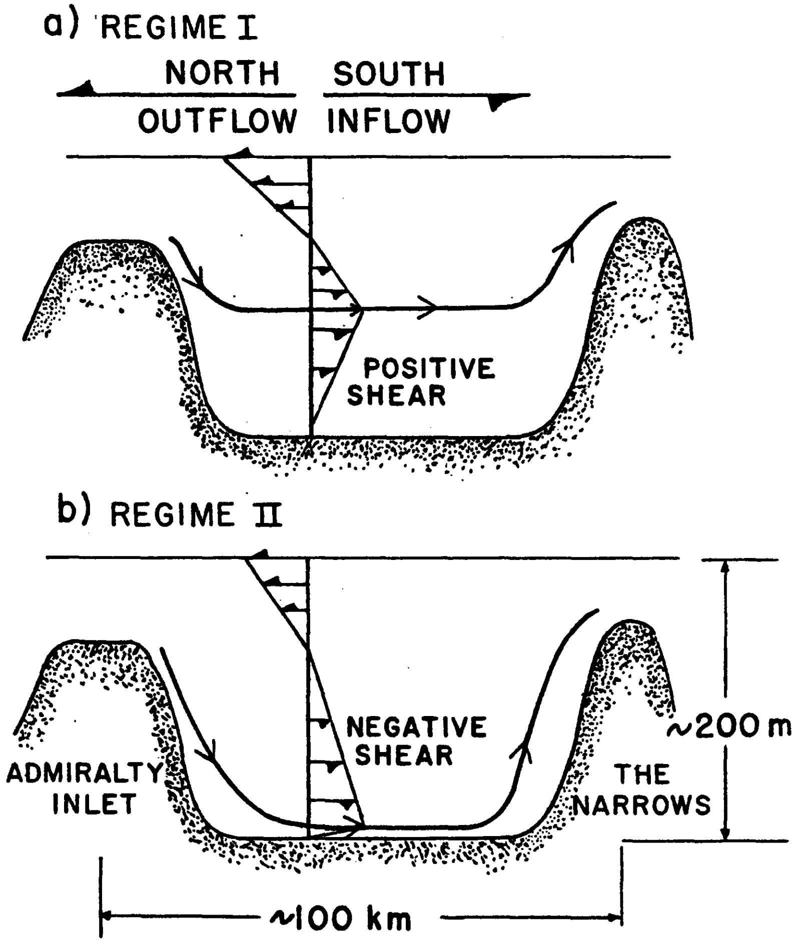

Fig. 3. Schematic velocity profiles in Puget Sound's Main Basin during Regime I (a) and II (b) superimposed on mid-channel depth between sills in Admiralty Inlet and The Narrows. In the lower layer having inflow the fastest currents occur near mid-depth in Regime I, and toward the bottom in Regime II. During the transition between regimes the deep velocity gradient (shear) changes from positive in I to negative in II.

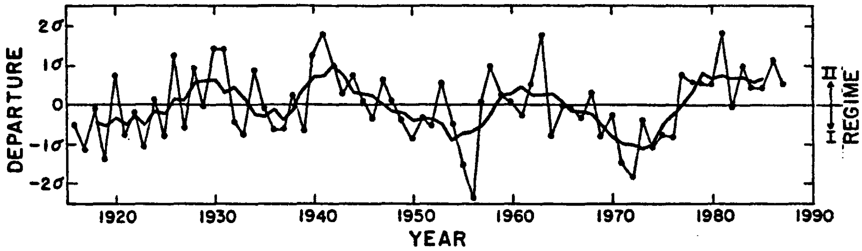

Fig. 4. Dimensionless time series (1916-'87) derived from coastal (Site 1) and Basin (Sites 6, 7) temperatures and snow depth (Site 11). Notation: dots, annual averages; heavier line, 5-year running average; δ, departure from eq. (1); σ, standard deviation; Sites, Fig. 1.

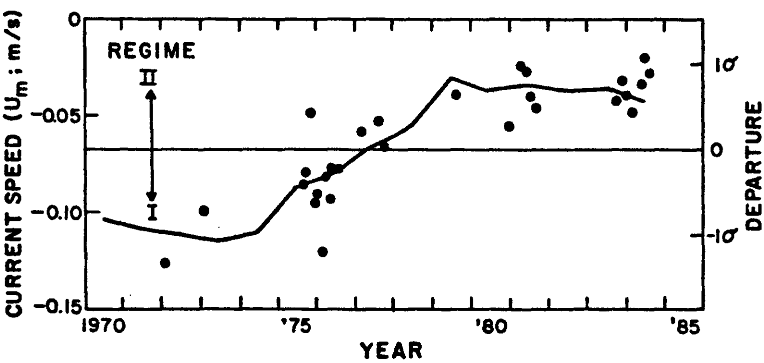

Fig. 5. Comparison of mid-depth current speed and the dimensionless time series (see Fig. 4). Notation: U_m, mid-depth along channel current speed at Sites 8, 9; dots, 28-day averages of mid-depth speed; line, 5-year running average of δ (departure computed from eq. (1)); σ, standard deviation.

Unusual Marine Organisms in Puget Sound:
Longterm Trends in a Poorly Understood Ecosystem

Alan J. Mearns[1]*

Introduction

Due to its great depths and open connection with the Pacific, Puget Sound is a habitat for sea and ocean life as well as the more familiar estuarine organisms such as herring, oysters and juvenile salmon. Like the open coast of the Pacific Northwest, Puget Sound harbors not only populations of shark, rockfish, sablefish, hake and flatfish but also deep-sea creatures such as lantern fish. Unfortunately, we remain rather ignorant about the natural history of these creatures, preferring instead to focus research on the more obvious and economically important estuarine and anadromous forms. Nevertheless, the true ocean organisms of the Sound may provide us with an important long-term sense of what is happening in the Sound.

The 1982-83 El Nino event served as a warning that the Sound is greatly influenced by oceanic processes (Schoener and Fluharty, 1985). Ocean fishes and invertebrates appeared in commercial and research catches or were observed by boaters during and following this major upheaval of the Pacific. Salmon strayed off their normal migratory paths and catches of some species such as squid changed markedly. These events and occurrences paralleled similar ones occurring all along the shores of Alaska, British Columbia, Washington, Oregon and California as well as the entire eastern Pacific Ocean. In short, Puget Sound was included in the changing Pacific phenomenon.

The problem is that the occasional El Nino event may not be the only major oceanic disturbance affecting marine life in the Northwest and in Puget Sound. In reviewing records of foreign organisms associated with the last El Nino event it became apparent that there were many strange occurrences of marine life during other years not experiencing major El Nino activity. (Mearns, 1988). Were such occurrences indicative of oceanic disturbances originating elsewhere such as in the northeast Pacific? If so, did they impact coastal areas such as Puget Sound? Indeed, should we look more carefully at what unusual organisms are telling us? Should we, in fact, monitor the ecology of Puget Sound sea life?

This paper attempts a small but hopefully provocative step in answering those questions by reviewing reports of unusual occurrences of conspicuous marine life along the Pacific Northwest coast and in the Puget Sound area. The report attempts to place local unusual occurrences in the larger context of long-term oceanographic and climatological changes.

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The report draws on a recently completed study of trends in unusual occurrences of marine life along the entire coast of the northeast Pacific from southeast Alaska to northern Baja California. Mearns, 1988).

Methods

Reports of rare and unusual marine organisms occurring along the Northwest coast during the past century were identified from various publications and personal contacts and interviews. The Northwest was defined to include the coastline from the California-Oregon border to approximately Juneau, Alaska., and including the inland seas of Puget Sound and the Straits of Juan de Fuca and Georgia. An unusual occurrence was one that was (1) a range extension, (2) classified as unusual by reporting authors or (3) a rare species in survey lists (such as Miller and Borton , 1980). Data were extracted according to methods cited in Mearns (1988). Each occurrence was entered into a record that included information such as the species, location, method of capture, and number of individuals.

Records were composited to develop files identifying individual species/year occurrences for each of five subregions (Oregon coast; Washington coast; Inland Sea, as defined above; British Columbia Coast; and southeast Alaska coast). These files were then sorted by year and the number of occurrences plotted to examine trends.

My assessment of trends began first by looking at patterns from records from the "Inland Seas" of Puget Sound and the adjacent straits, Next, data from the entire Northwest were examined to see if similar patterns prevailed.

During the course of the survey it became apparent that knowledge was lacking about the "unusualness" of some apparently-rare organisms such as deepsea and mesopelagic fish. These were excluded from the analysis, but included in the discussion.

Northwest and Puget Sound Records

A total of 202 records of unusual occurrences in Pacific Northwest waters were developed for 40 species of conspicuous (easily identified) marine organisms including fishes (24 species), elasmobranchs (7), non-vertebrates (8) and reptiles (1). The collection covered the period 1883 through 1987.

Within the inland seas of Puget Sound and the straits I developed 77 records of notable occurrences for 4 species of elasmobranchs, 11 species of fish, four non-vertebrates and one reptile covering the period 1883 to 1987 (Table 1). The organisms actually captured within Puget Sound ranged from tunas (Pacific bonito, *Sarda chiliensis*) to Pacific electric ray (*Torpedo califorica*, which shocked several collectors). When pooled by year and plotted, several features of these data are apparent. Most obvious are peaks in occurrences of unusual organisms during the well-known El Nino years of 1957-58 and 1983 (Figure 1). In addition, there appear blocks

Table 1. List of some species involved in unusual occurrences in Puget Sound and the Straits of Juan de Fuca and Georgia (southern).

Common Name	Scientific Name	Years of Occurrence
Thresher shark	Alopias vulpinus	1949,72
Pacific electric ray	Torpedo californica	1964,65,71,72,79,86
Basking shark (others)	Cetorhinus maximus	1939,48,58,63,72,
Salmon shark	Lamna ditropus	1963,64
Pacific bonito	Sarda chiliensis	1900,19,62,63,64,72
California tonguefish	Symphurus atricauda	1984
Pacific pompano	Peprilus simillimus	1903,08,40,41,46-49,83,85
Ocean sunfish	Mola mola	1919,26,59,62,83
White seabass	Atractoscion nobilis	1883,1957,58
Pacific barracuda	Sphyraena argentea	1904,58, (more)
Pacific sardine	Sardinops sagax	before 1892;1916,1958
California lizardfish	Synodus lucioceps	1975,83,84,87
Jack mackerel	Trachurus symmetricus	1975,83
Pacific mackerel	Scomber japonicus	before 1919,1963
Pacific pomfret	Brama japonica	before 1884, 1963
Market squid	Loligo opalescens	1927,40,41,58,59,62,82, 83
Purple sailor	Vellella	1934, 57(?),83,84
pteropods		1958 .
red tides (PSP)	Gonyaulax	1945,59,78,80,81
sea turtle		1986

of contiguous years with unusual occurrences including 1940-41, 1945-49, 1962-65, 1971-72 and 1978-84.

Although a minimal amount of data is included in this assessment, the resulting patterns are strikingly similar to those from the larger more geographically extensive data for the entire Northwest coast. As shown in Figure 1, the same year groupings of unusual occurrences appear for the entire Northwest coast. In addition, the potential magnitude of the 1982-83 El Nino-associated reports becomes quite evident and new groups of reports appear for the late 1920s, mid 1930s. and late 1940's And while there are few years without reports, they too fall into groupings such as the early 1920s the early 50s and the late 60s.

Comparison with the Northeast Pacific: The Odd Years

The patterns reported above agree with those analyzed in detail for the

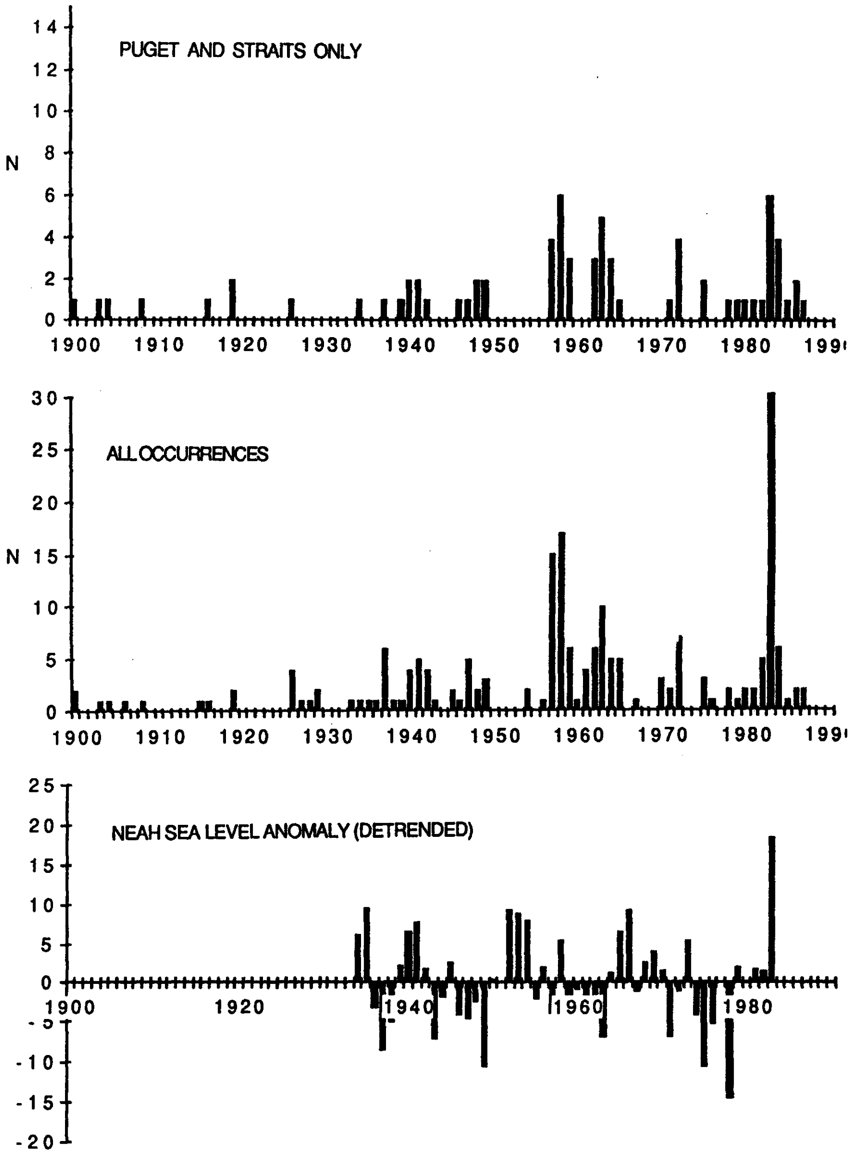

Figure 1. Annual variations in reported occurrences of unusual marine organisms for inland seas of Puget Sound and the Straits of Juan de Fuca and southern Straits of Georgia (upper) and for the entire Northwest coast (middle) and annual average deviations in sea level. at Neah Bay

entire northeast Pacific coast (Mearns, 1988). That study involved 577 records of occurrences of 161 species of invertebrates, fishes and reptiles which various authors reported as unusual. The number of reported occurrences increased over time from about 2.25 per year in the early 1900's to 16.5 in the 1950s dropping to 10.5 per year in the 1960s and 5.8 per year in the 1970s. The long-term rise (1900 to 1950) occurred for both southerly occurrences of northern species and northerly occurrences of southern species. From these data 13 years were identified with significantly higher-than-average numbers of unusual occurrences.

Nine of these years (1918, 1919, 1931, 1937, 1947, 1958, 1959, and 1965) were clearly dominated by unusual northern occurrences of southern warmer water species, one (1915) by extreme southern occurrences of northern species and three (1963, 1948 and 1951) by mixes of southern, northern and oceanic species.

Of these thirteen years, only six (1918, 1931, 1948, 1957, 1958 and 1959) were also physically unique with respect to Southern California records of sea surface temperature and sea level, and with respect to occurrences of El Nino events: five (all but 1948) were clearly warm-water years along much of the coast. However, 7 years (1915, 1919, 1937, 1947, 1951, 1963 and 1965) were not physically unusual with respect to conditions off Southern California. All but 1915 involved unusual northerly occurrences whereas 1915 was a year of numerous southerly occurrences (salmon in Southern California). Since the only physical data invoked in that study were from Southern California, the possibility remains that conditions further north, and unconnected with El Nino events, were unusual in their own right.

It is now evident that at least the 1963 occurrence of southern species in Puget Sound can be partially explained. As reported recently by Dodimead (1985) 1963 was indeed an unusually warm year as recorded by temperature gages along southern Vancouver Island. Indeed, the entire period 1957 through 1967 appeared to be unusually warm in waters of the Pacific Northwest. However, the early 60s did not experience the elevated sea level usually associated with El Nino events (bottom of Figure 1). If adequate records can be identified it may be possible to determine if Puget Sound experienced the same phenomenon and, indeed, if there are significant oceanic events originating in the Northwest independent of El Nino events.

The Deep Sea Fauna of Puget Sound

During the course of this investigation it became apparent that several species of deep sea and mesopelagic fish captured in Puget Sound could not be readily analyzed without careful accounting for sampling effort.

Included in Miller and Borton's (1980) catalogue of Puget Sound fishes are six species: longnose lancet fish; slender barracudina; California headlight fish; Northern lanternfish; and blue lanternfish. In addition, Hart (1973) lists nearly a dozen other deepsea and mesopelagic fish from the Straits of Georgia. He also refers to a Fraser Counter-current that at times may bring such organisms to the Vancouver shoreline. These may not be unusual occurrences, but fortuitous captures of a resident mesopelagic fauna of Puget Sound and the straits.

Discussion

The trends and patterns descibed here are probably only minor manifestations of larger, yet to be discovered oceanic processes that affect all marine life in the Northwest and Puget Sound. It may be that fluctuations in important fishery stocks and landings have their origin in processes that also deliver to our shores the rare and unusual.

One process that is clearly underway is global warming as a result of the "Greenhouse Effect". I am not aware of the extent to which Puget Sound researchers and monitoring communities are planning to account for local ecological changes resulting from this process or indeed if anyone has even attempted to predict what might happen in the Sound. How will rising sea level and changing tides affect flushing and circulation in the Sound? Will red tides increase or decrease as a result? Will currently common species be replaced? It may be that unusual occurrences of exotic organisms may provide warning of pending change, provided we understand what is now "normal". To emphasize this point, it can be shown that a tropical fish, the finescale trigger fish, *Balistes polylepis*, has been undergoing a long-term series northern range extensions from San Pedro, CA in 1931, continuing with increasingly northerly records in 1946 (Santa Barbara), 1951 (Monterey), 1958 (Santa Cruz), 1959 (San Francisco) and, more recently, 1983 (Yaquina Bay) and 1984 (Willapa Bay). Perhaps there are many indicator species that we should be monitoring now.

This brief review suggests to me that much needs to be learned about the ecology of the main body of Puget Sound and the Straits of Juan de Fuca or how those ecosystems respond to events of oceanic proportions. Our current knowledge may be limited only in part by a lack of data : there are numerous catch statistics and observations developed by the Washington Department of Fisheries and regional universities but there are no routine Puget Sound ecological monitoring programs other than the voluntary study of Nichols (this symposium). A second constraint may be the lack of a unified theory that prompts an ecological surveillance. A third may be a lack of a regional journal for scientists to publish such observations and encouragement to do so.

Acknowledgements

Many thanks to Steve Hulsman and Paul Clark, Washington Department of Fisheries, for bringing to my attention recent captures of odd fish, and to Dr. Ron Reed, Pacific Marine Environmental Laboratory, NOAA, for providing the processed sea level data. Finally, I appreciate the stimulating discussions over the years with Drs. Curtis Ebbesmeyer, Fred Nichols.Amy Schoener, Jim Allen and Howard Harris. We a lot more of this.

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LONG-TERM CHANGES IN A DEEP PUGET SOUND BENTHIC COMMUNITY: LOCAL OR BASIN-WIDE?

Frederic H. Nichols *

Abstract

Near-continuous quantitative sampling of the macrobenthos at a 200m-depth site off Seattle has demonstrated that species composition has remained relatively stable since 1963, with the clam Macoma carlottensis as the numerical dominant. Since the mid-1970's, however, total abundance has been increasing and numerical dominance among species has shifted markedly over irregular, multi-year intervals to species that were previously rare. That is, Macoma began to share dominance with a succession of species (the polychaetes Ampharete acutifrons and Pectinaria californiensis, the clam Axinopsida sericata, the ostracod Euphilomedes producta, and the cumacean Eudorella pacifica) that had been, until their recent irruptions, minor components of the community.

Preliminary data from samples collected since 1969 at two other sites suggest that some of the recent individual species irruptions at the 200m site (e.g., Ampharete, Pectinaria, Euphilomedes, Eudorella) occurred simultaneously at one or both of the other two sites. Hence, these changes were apparently basin-wide rather than localized.

The increased incidence, in the last ten years, of irruptions of previously minor species, and the concomitant increase in overall macrofaunal abundance remain unexplained by this study, but hypotheses of a changed physical environment and increased productivity should be examined. Long-term monitoring of the benthic environment at open water sites like those used in this study will provide necessary controls for shorter-term monitoring of nearshore sites that are more clearly affected by human activity.

Introduction

The Puget Sound benthos (that community of invertebrates living in bottom sediments) has been the subject of numerous surveys since the 1920's (e.g., see Lie, 1968 and 1974 for references to earlier studies). We have learned from the many studies that species composition in Puget Sound is roughly determined by water depth and sediment particle size and that the occurrence of common species can be reasonably well predicted. It is not possible, however, to demonstrate any evidence that the benthos of Puget Sound has changed

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perceptibly since the first samples were collected in the 1920's. This is the case, in part, because sampling locations, methods, sample handling, and data reporting varied greatly from study to study, because abundance of a given species varies widely in both space and time even within a limited range of depth and grain size, and because the common species collected during the early surveys remain common today. The few studies that have included sampling at fixed sites through time, e.g., Lie (1968), Lie and Evans (1973), and Nichols (1975, 1985), have shown that while community composition remains reasonably stable, numerical abundance of individual species at any location varies greatly over both seasonal and annual time scales, thus further confounding attempts to compare recent with past data sets.

In the context of increasing human influence on Puget Sound, it is important to determine to what degree biotic communities have changed through time. Benthic invertebrates, because of their sessile habit, can provide a continuing record of the effects of changes in their environment through changes in species composition or abundance (Bilyard 1987). Needed, therefore, are data consistently collected over many years at fixed sites to quantify the limits of natural variation within a community and its environment and, thereby, to reveal trends or permanent changes.

The purpose of this paper is to describe results of a continuing long-term study, initially described by Nichols (1985), in which patterns of variation have been characterized at three open water sites (locations well removed from major human influence) and several unexplained trends have been detected.

The Study

Among the many locations where samples of the benthos have been collected over the decades, only three sites have been sampled continuously for periods sufficiently long to characterize typical year-to-year variation in the community: Station 1 at 35 m water depth, Station 2 at 200 m depth, and Station 3 at 250 m depth (Figure 1; see Nichols, 1975). Station 2 has been sampled nearly continuously for 25 years.

Nichols (1985), reporting on the data collected at Station 2 through 1983, showed that since the mid 1970's numerical dominance changed irregularly from species to species over multi-year periods, and that total abundance was increasing with time. Further sampling and analysis has provided additional evidence that the community, subject to continuing irruptions of previously uncommon species, is gradually changing with time and that some of the changes are not restricted to station 2. *Macoma carlottensis* has been the numerically dominant species since the beginning of the study in 1963 (Figure 2). *Macoma* was absent only during 1969 and early 1970 (there are no data from 1968 to determine when the decline in this species began) when it was apparently replaced (through an as yet unknown mechanism) by the polychaete *Pectinaria californiensis* (Figure 2). Beginning in the mid-1970's, dominance shifted from one species to another, with intermittent irruptions of *Macoma*, the polychaete *Ampharete acutifrons*, the clam, *Axinopsida sericata*, the ostracod *Euphilomedes producta*, the cumacean *Eudorella pacifica*, and

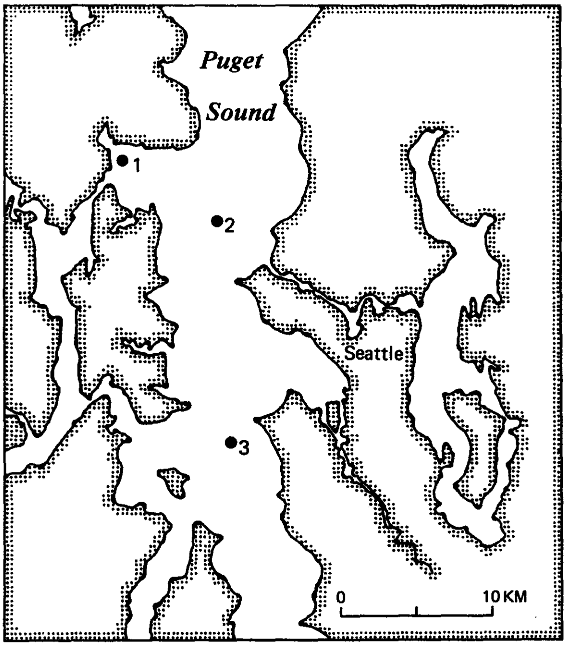

Figure 1. Central Puget Sound, with locations of three long-term benthos sampling stations.

the polychaete Pectinaria (Figure 2; Nichols unpublished data). As a consequence of these unexpected species irruptions, total abundance in the community has steadily increased with time since the mid-1970's (Figure 3).

Because we lack data for several 1- to 2-year periods between 1965 and 1973 (Figure 2), it is not possible to say definitely that the events of the past 10 years are a significant departure from the situation prior to the mid-1970's. It is certainly possible that Ampharete, Axinopsida, Euphilomedes, and Eudorella were more abundant during the unsampled periods, although the intervening data do not support this possibility. The data suggest, rather, that a subtle transition in this community toward larger populations and frequent shifts in dominance among species has been occurring, trends that are clearly apparent in the unbroken suite of data gathered since 1973.

An obvious question is raised by the results from this single site: are the observed changes restricted to this site (i.e., influenced by local factors) or are they representative of more widespread community dynamics? While data from two other stations, sampled since the mid-to-late 1960's, are just now being analysed, early results suggest that at least some of the changes seen at station 2 are reflected in the other two stations as well. As examples, the polychaetes Pectinaria californiensis and Ampharete acutifrons

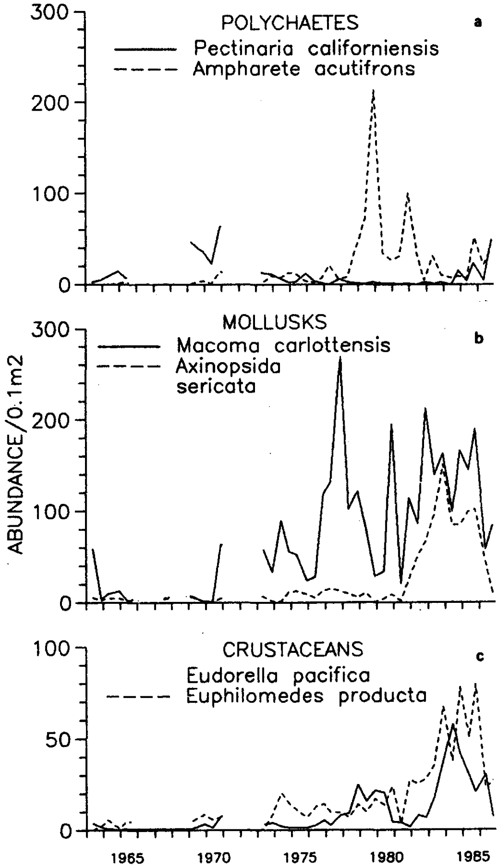

Figure 2. Mean abundance of benthic species that have been abundant at Station 2 at some time during the 24-year period of observation. See Nichols 1975, 1985 for sampling methods.

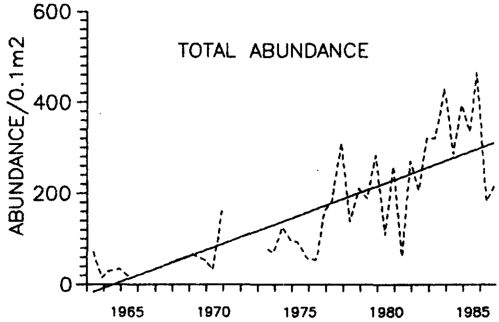

Figure 3. Combined abundance of the species shown in Figure 2 (dashed line), with linear best fit of data (solid line).

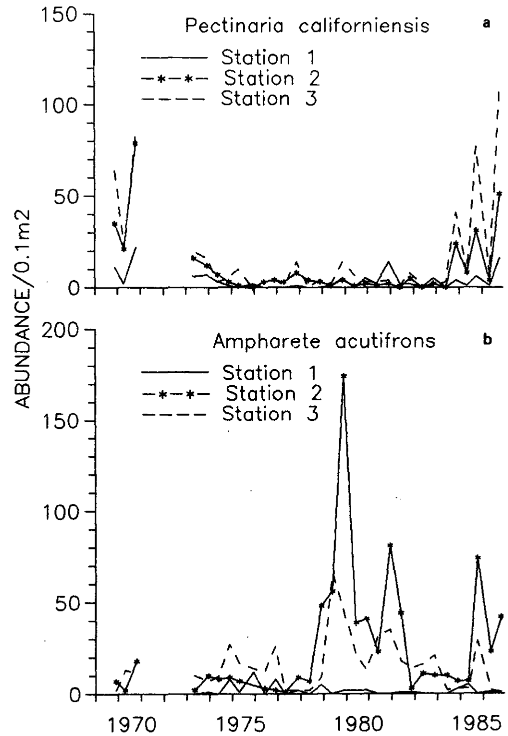

Figure 4. Abundance of species common to Stations 1, 2, and 3.

irrupted simultaneously at the two deep sites, and Pectinaria abundance at the shallow site also increased during the irruptive periods (Figure 4). On the other hand, abundances of Macoma carlottensis and Axinopsida sericata varied widely from station to station through time.

Discussion

The results of this ongoing study demonstrate that the benthic community of Puget Sound is characterized by very large interannual variations in the abundance of a few species, typically as irregularly occurring irruptions of several years duration. Because some of these irruptions occurred simultaneously at all sites, we can tentatively conclude that the maintenance of these communities may be dependent, at least in part, on processes that are basin-wide.

While these results remain unexplained, two hypotheses are suggested: (1) physical processes, such as water circulation and mixing that affect survival and recruitment of larvae and juveniles, have changed and (2), the waters of the Puget Sound basin have

become more productive, and thus support higher abundances of benthic invertebrates.

Ebbesmeyer et al. (this volume) provide evidence that circulation in the main basin of Puget Sound can change over decades: there is a major difference in circulation patterns between the decade before the mid-1970's and the decade since then. Possibly, a major shift in currents can result in a change in transport processes that alters the mixture of larvae being recruited to the bottom at any site. For example, the predominance of up-estuary flow along the bottom of the main basin during the past decade (as opposed to the predominance of flow at mid depth during the previous decade) could have enhanced larval dispersal near the bottom. In the absence of data on invertebrate larvae in Puget Sound, however, this hypothesis remains speculation.

There is also no clear evidence from existing data that the waters of the Puget Sound basin, with time, have become more productive and, as a result, stimulated an increase in benthic invertebrate abundance. However, given the increased human population in the Puget Sound area and the concomitant increased rate of waste input, it is possible that gradually increasing nutrient concentrations could cause an increase in overall water column productivity and the subsequent enhancement of organic matter supply (food for the benthos) to the sediment surface.

An hypothesis of gradually increasing productivity, if supported by data from other studies, should be examined. Initial comparisons could be made between present conditions (e.g., nutrient levels, phytoplankton abundance, sediment organic content, and benthic oxygen demand, etc.) and those measured a decade or two ago (e.g., Collias et al., 1974; Winter et al., 1975; Pamatmat, 1971). While such retrospective studies may provide preliminary evidence of the presence or absence of major long-term changes, comparisons between separate short-term (1- to 2-year) studies may produce misleading results; as can be seen from the data presented here, results from a short study may not be representative of longer term "average" conditions. The establishment of routine, long-term water column and bottom monitoring (e.g., of nutrients, oxygen, phytoplankton abundance [chlorophyll], sediment organic matter, and benthos, as well as contaminants; see Chapman et al., 1987) at a number of open water sites such as those discussed here, will be necessary to provide quantification and interpretation of natural (background) variability and trends within the Puget Sound benthic community. The results from open water sites will also provide the essential "control" for shorter-term monitoring results from nearshore sites that are expected to be most strongly affected by human activity (see Bilyard 1987). Such a network should allow us to develop reliable evidence of the presence and significance of water quality trends in Puget Sound, including evidence of improvements resulting from regulatory actions.

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Trends in Abundance of Economically Important Marine Fish in Puget Sound

Gregory G. Bargmann*

Introduction

The Washington Department of Fisheries routinely assesses the abundance of economically important species of marine fish in Puget Sound. These assessments are largely done for fisheries management purposes. However, they do provide insight into the abundance of major fish species and into the interannual variability of abundance.

These assessments have increased as fishing pressure has increased in Puget Sound. The longest time period for which some idea of abundance can be inferred is thirty to forty years and, in most cases, is nearer to ten to fifteen years.

Methods

The Department of Fisheries estimates fish abundance in two general ways; indirect and direct. Indirect methods rely on fishermen, and their fishing effort and resultant catch, to provide insight on fish abundance. Direct methods involve department employees going out and actually measuring the amount of fish present at a certain time. Generally these direct measurements occur when the fish are spawning or just before they spawn because, at these times, the fish are congregated and their abundance is most easily and accurately measured.
For each species discussed in this report, a brief summary of the method used to estimate abundance is given. Additionally, a reference is listed for more detailed information.

English sole

English sole (*Parophrys vetulus*) is one of the most important species in the commercial fisheries and one of the fish species most associated with contamination studies in Puget Sound. Abundance of English sole in Puget Sound is monitored through the landings of the otter trawl fishery. Landings of English sole from Puget Sound have been as high as 2.4 million pounds annually. However, the amount of fish landed has declined in recent years. Concurrent with the decline has been a decline in the catch rate (Figure 1). This decline has been most evident in the central Puget Sound region (Quinnell, 1984).

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Pile perch

Pile perch (*Rhacochilus vacca*) is an important species in both commercial and recreational fisheries in Puget Sound. The largest fishery for pile perch is the beach seine fishery. Performance of the beach seine fishery indicates a decline in both landings and catch rates of pile perch. These declines are thought to be due to decreased availability of pile perch (Quinnell, 1986).

Pacific whiting

A population of Pacific whiting (*Merluccius productus*) spawns in the Port Susan area near Everett and is subject to a commercial fishery. The abundance of this stock has been monitored using sonar techniques since 1979 (Boettner, 1984).

Results indicate that this population has been declining in size in recent years from a peak biomass of 45 million pounds in 1983 to 12 million pounds in 1987.

YEAR	Whiting Estimated biomass (millions of pounds)
1979	22.9
1980	26.8
1981	33.1
1982	29.1
1983	45.1
1984	31.2
1985	31.2
1986	18.0
1987	12.3

The predicted biomass for 1988 is between 10 and 14 million pounds (Stick et al.,1987).

Pacific cod

Pacific cod (*Gadus macrocephalus*) in Puget Sound are near the southern end of the geographical range and their populations tend to vary greatly in Puget Sound (Pedersen and DiDonato, 1982). In most areas, changes in population size have been without trend (Pedersen and Bargmann, 1986). However, in recent years, declining trends in abundance have been seen in Pacific cod in central Puget Sound (Wildermuth, 1986; Hulsman, 1988).

Lingcod

Lingcod (*Ophiodon elongatus*) is an important species in both recreational and commercial fisheries. Their population, as measured by fishery performance, declined sharply in the mid 1970's, especially in Hood Canal and Puget Sound south of Port Townsend. A series of severe fishery restrictions were implemented. Lingcod populations apparently rebounded sharply in the 1980's as a result of these restrictions (Bargmann, 1985).

Herring

Pacific herring (*Clupea harengus*) spawn in specific locations throughout Puget Sound (Trumble, 1983). The spawning season begins in January and continues into June. Approximately 15 thousand tons of herring spawn annually in Puget Sound at several major spawning sites (Penttila et al.,1986). While there is considerable interannual variation in the amount of spawning at any one site, the total number of spawners in central Puget Sound and Hood Canal has been relatively stable. The population which spawns in northern Puget Sound in May and June has been in a period of decline (Day, 1987).

Rockfish

Rockfish (*Sebastes* sp.) are important components of the recreational fishery and are of minor importance to the commercial fisheries. The catch by the recreational fishery has increased by nearly an order of magnitude between the mid 1970's and the mid 1980's but the catch rate (number of fish caught per fishing trip) declined during that time. The growth in landings was largely the result of increased fishing effort (Palsson, 1987).

Discussion

All of the fish species discussed are subject to rather intense fisheries; either recreational or commercial or a combination of both. While monitoring of these resources has not been ongoing for long periods of time, several points can be made:

1. Fish populations do fluctuate. The amount of fluctuation depends on the particular species. Fish, such as whiting and Pacific cod, can show wide variations in abundance from year to year while species such as English sole are more stable.

2. Fishing can have an important impact on fish populations.

3. Puget Sound still supports relatively large fish populations. Annual catches of about 1 million pounds of English sole and one quarter of a million rockfish can be made and 15,000 tons herring spawn annually. Puget Sound is still a productive system. However, in recent years, the trend of abundance for most of the important marine fish species has been downward.

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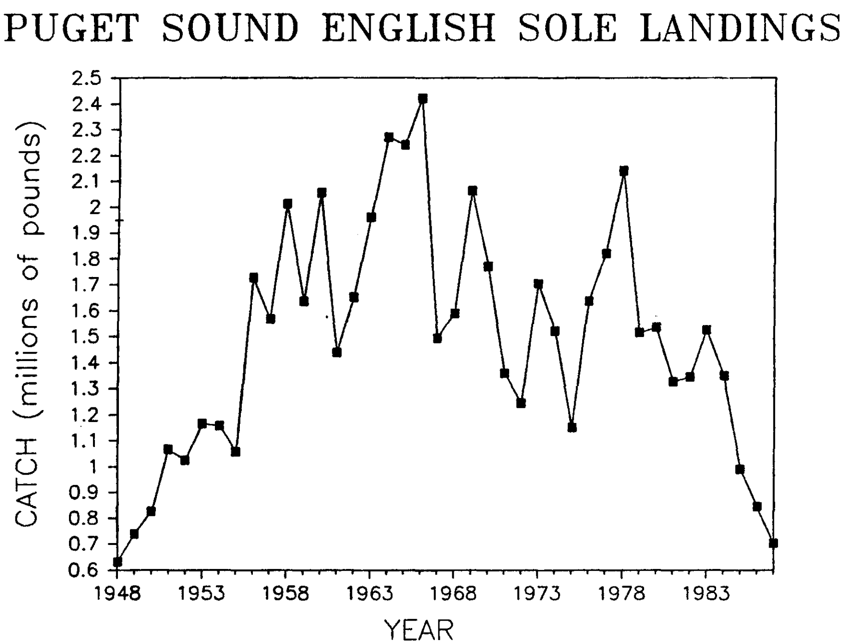

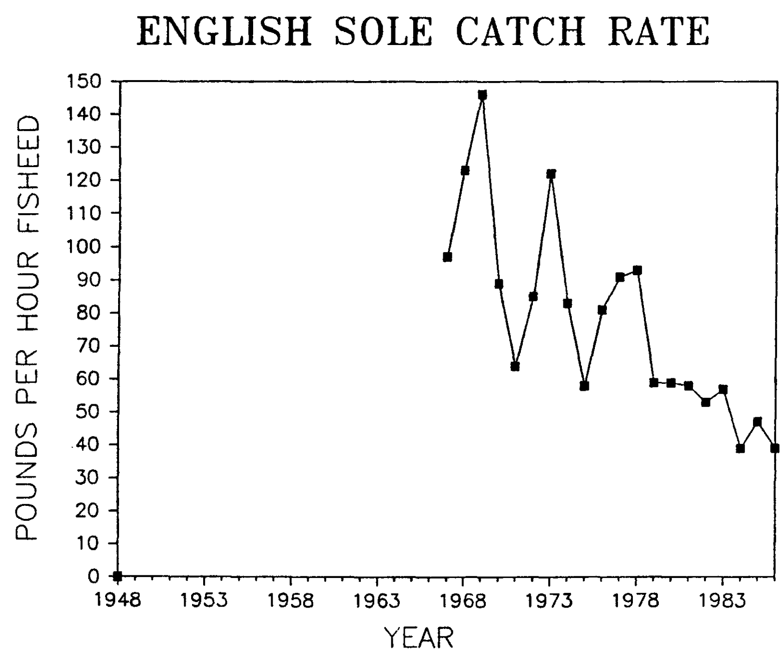

Figure 1. English sole landings and catch rate from the Puget Sound otter trawl fishery.

Characterization of Puget Sound Marine Fishes for the EPA Bay Program

Lawrence L. Moulton[1] and Bruce S. Miller[2]

Introduction

One of the main phases of the EPA Bay 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. The objectives of this synthesis and analysis are to identify spatial and temporal changes in the estuarine system and evaluate probable causes for these changes. One of the initial steps in the characterization process is to identify the existing data and determine which portions of the available data are needed to adequately describe the resources of the study area.

The ultimate objective of this project is to analyze for long-term changes in Puget Sound marine fishes based on the available data. Analyses of distributional differences in Puget Sound have been conducted and notable patterns exist (Wingert and Miller 1979), but those analyses did not incorporate time into the evaluation. The initial objective of the current study, reported on here, was to inventory the more extensive historical data sets to evaluate their suitability for use in the time-trend analysis. Information on location, date, gear used, number of sets made, depths sampled and types of data recorded were reviewed and included in the inventory to determine if these data were available in sufficient temporal and spatial coverage and of sufficient quality to evaluate trends in selected species or populations over time. An additional benefit of the project is the identification of the various collection methods used over the years, which can be used to help define standardized methods so that future investigations can be conducted in a compatible fashion.

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Methods

The inventory was conducted by:

1. Interviewing people from various organizations who are familiar with or routinely work with the type of data needed for the characterization study and

2. Reviewing historical data sets identified through the interviews.

Prior to initiating the data survey, an advisory work group was formed of people familiar with marine fish investigations in Puget Sound, including representatives from resource agencies, private research groups and the University of Washington, to identify possible data sources. These sources, and others previously known by the investigators, were investigated to evaluate their suitability for inclusion in the characterization study.

The data evaluation focused on the objective of the characterization phase, which is evaluating trends over time. The main criteria used for selecting a data set for further evaluation and possible inclusion in the characterization phase were:

1. Three or more years of information using consistent methods at a specific location were available; or

2. The data set supplements similar information or extends the period of record from other sources;

3. The data set appeared to have the detail needed to reveal changes over time in species composition, abundance or size structure of marine fish in a specific area; and

4. The group of fish species being evaluated for change are not overly affected by fishing pressure.

The twelve regions of Puget Sound utilized by DeLacy et al. (1973) to evaluate species distribution were used to evaluate the geographic distribution of the available data.

Results

Data available from long-term University of Washington investigations conducted by Drs. DeLacy, English and Miller from 1949 to the present appear to offer the best long-term data available for certain locations throughout Puget Sound. Other data sets, however, also provide quite useable information. Of these additional data sets, the Washington Department of Fisheries trawl surveys provide considerable long-term coverage of regions in northern

Puget Sound. In addition, the Department of Fisheries herring spawning ground surveys contain annual estimates of spawning density of Pacific herring at sites around Puget Sound. A description of the coverage and methods used by the various researchers follows:

College of Fisheries (COF) trawl logs

These records, mostly from 1949 to 1976, were primarily collected or recorded under the direction of Dr. Allan C. DeLacy. Coverage ranged from Case Inlet in southern Puget Sound to Orcas Island and Bellingham Bay in northern Puget Sound with a substantial effort in the central Puget Sound region. Gear used were a variety of otter trawls; however, most of the more useable time series information was taken with the basic research trawl, which had a 1.25 inch stretched mesh cod end. Other nets used were similar in overall dimensions but the cod ends were usually 3.5 and 4.5 inches stretched mesh.

Data commonly recorded included species occurrence and usually some indication of relative abundance, including nearly complete counts, the exception being species that were highly abundant in a haul (i.e. hundreds or thousands of individuals). In many cases length frequencies of the dominant species were recorded. From 1965 to 1976 there was a series of training cruises that utilized the basic research trawl and re-visited the same six locations. There were normally two, and up to four, trips per year in this time period covering sites in central and northern Puget Sound. These cruises normally had reasonably complete data sets with total counts and length measurements.

Dr. English trawl logs

These records, from 1964 to 1978, were all collected with a 16 ft semi-balloon otter trawl attached to a 10 ft (3 meter) beam. The body of the net was 1.25 inch mesh with a 0.25 inch mesh cod end liner. Data collected included total counts and length measurements of captured fish, information on crabs and shrimp was also a primary concern. Disease information was also collected for many of the sampling sites. The best time series of information is from Port Gardner, which was sampled from 1965 to 1978, and adjacent sites at Mukilteo and Tulalip sampled from 1973 to 1977. Some of the areas surveyed overlap the locations and times of College of Fisheries training cruises, thus there is an opportunity to compare the species and sizes captured by the different gears.

Dr. Miller trawl logs

These records begin in 1969 and are continuing. Two gear types have been used: from 1969 to 1980 sampling was conducted with a 16 ft semi-balloon otter trawl (0.25 inch

stretched mesh cod end) attached to otter boards, while after 1980, a 25 ft otter trawl has been used. Information routinely collected included total counts, length measurements and disease incidence by species. Most of the information has been collected in the central Puget Sound region, primarily related to investigations near Metro's present or planned outfalls or nearby control areas (Table 6). More recent investigations have included studies in Commencement Bay, Elliott Bay, Port Gardner and Saratoga Passage. The latter two locations provide possible ties to the Dr. English trawl series, particularly since the sampling in 1986 used both a 25 ft otter trawl and a 10 ft beam trawl.

Drs. DeLacy/Miller beach seine logs

From 1949 to 1967 beach seine sampling was conducted almost annually at Golden Gardens, often during an extreme tide cycle to examine tidal influences on fish distribution. The gear consisted of either a 60 ft or 120 ft beach seine constructed of 1.25 inch stretched mesh wings with a 0.75 inch stretched mesh bag. Data collected were total counts and, usually, length measurements and total weight of each species.

Similar methods were used at other beaches in central Puget Sound, including Alki Point, West Point, Smith Cove, Point Pully, and Seahurst Park. In the mid to late-1970's, substantial beach seine sampling was conducted at shoreline sites around the San Juan Islands as part of the DOE Puget Sound Baseline Program (1974 to 1976) and along the Strait of Juan de Fuca as part of the MESA Puget Sound Project (1976-1979).

Dr. DeLacy/Miller flatfish ichthyoplankton sampling

This series was compiled between 1955 and 1985 and consisted of collecting flounder eggs and larvae in Elliott Bay during the spawning season as part of a course on early life history of marine fishes. Gear used included 0.5 meter plankton nets, 20 and 60 cm bongo nets and various experimental nets and plankton pumps. Information collected included number of eggs per tow, which was converted to density of eggs, with sampling occurring at a variety of depths. The data set may provide interesting information on the consistency of flatfish spawning in an area adjacent to heavy industrial development.

Friday Harbor Marine Lab logbooks

The information on marine fish from the Friday Harbor logs consists of four types of data: (1) otter trawl records, (2) beach seine records, (3) night light sightings and (4) tidepool records. The logs cover a period from 1950 to 1987, with most of the records being entered on a two year

cycle because the fish ecology course alternated annually with the biological oceanography course. The locations covered vary by gear type, since each of the survey methods samples totally different habitat.

Washington Department of Fisheries

The Washington Department of Fisheries has long-term data on a number of marine fisheries. The most appropriate data sets appear to be information on marine fish collected in the trawl fishery and herring spawning surveys.

The trawl survey data consist of summaries of logbooks maintained by the fishermen since the mid-1950's. Information consists of catch by species and effort for each fishing area. Most of the data are from the Gulf of Georgia, Northern San Juans, Bellingham Bay, Saratoga Passage, Holmes Harbor and Discovery Bay, since these are the areas of greatest effort. Hood Canal was an important area in the past, but trawling is discouraged in this area at present. There was generally low effort in central and southern Puget Sound, in part because of the high incidence of parasites in bottomfish.

Surveys of representative herring spawning areas have been made annually for the past ten years. The surveys estimate the number of tons of spawning fish in each year and are made to coincide with the estimated time of peak spawning. Maps are produced of the areas used. In addition, there are acoustic estimates of adult herring near the spawning areas. Herring spawn in shallow water and the spawning areas are highly vulnerable to surface contaminants, thus the surveys might quickly detect changes in habitat use by spawning fish.

Miscellaneous data sources

Aside from the long-term data sets identified above, there are a number of short-term studies that have been conducted in a number of the regions that can assist in interpreting long-term trends. These short-term studies provide additional detail on marine fish populations within a region and help extend the period of record provided by the long-term data sets. Often these short-term studies occur as reports or publications.

Recommendations

We recommend continuing with the characterization process because of the long-term series available for several of the regions, particularly Central Puget Sound, Whidbey Basin, Port Orchard and the San Juan Islands. It is recommended that the following priority be used for

analysis of data for the characterization of Puget Sound fishes:

1. Research otter trawl data sets, focusing on Port Orchard, Port Gardner and Bellingham Bay, with further evaluation of Port Madison and Case Inlet data

2. WDF herring spawning survey data

3. Elliott Bay ichthyoplankton data series, with possible inclusion of Port Orchard and central basin data

4. Research beach seine data focusing on the Golden Gardens data sets

5. WDF commercial trawl data, focusing on Pacific cod, English sole, rock sole, sand sole and starry flounder

6. Friday Harbor logbook data, focusing on sites with long-term sampling series by a consistent method

Research trawl logs have the best time-series information and can be supplemented with some of the additional data from other sources. The WDF herring spawning surveys provide a good opportunity to follow a time-series of the critical life stage for an individual species at widely separated locations and deserve special treatment in a characterization document. Similarly, the flatfish spawning areas at Duwamish Head and Port Orchard deserve similar treatment. The Golden Gardens beach seine data provide a long-term record of nearshore habitat use in an area that has been increasingly developed, and cover the construction period for the Shilshole Marina and breakwater. As the study progresses, other specialized studies that document critical habitats may become apparent and these could be incorporated.

We predict that a time series analysis of marine fish data sets will elucidate long-term trends in Puget Sound fish assemblages and will be of significant value for establishing a baseline against which the results of future monitoring efforts can be compared and evaluated. The review of the data already indicates that while many of the beach seine and trawl sites were regularly sampled from the 1950's to the 1970's, there has been a less complete record for the last ten years as the studies have become more oriented to short-term projects. Monitoring efforts that include sampling of marine fish should consider incorporating the sites with long-term baseline information into the study design to provide some means of evaluating future changes that may occur.

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Summary Statement

Curtis C. Ebbesmeyer*

Eight papers were presented showing long time series of physical, biological, and chemical properties of Puget Sound and approaches. In Table 1 I've selected six time series from the papers and noted the approximate ranges of the quantities and years sampled. It is obvious that many properties cycle over large ranges at periods of several years to centuries. Most likely many of the cycles are associated with climatic fluctuations. It is difficult, particularly for biological properties, to separate man's influence from other natural variability.

A challenge to regulators occurs because of the mismatch in the timing of the natural cycles versus funding of man's investigations. Usually funding for particular efforts lasts only a few years. Conclusions drawn from data sets collected over several years may be misleading because of the long-term cycles. For this reason it is important to maintain long records of conditions in Puget Sound.

During the meeting and in discussions held shortly afterward, it became apparent that these and other long time series need to be combined on common scales so that they may be easily compared. There are other useful data contained in available studies of glaciers, tree rings, and sediments extending back several hundred years. If these proxy data were combined with modern data measured with instruments, it seems highly likely that the climatology, hydrology, and oceanography of the Puget Sound region could be reconstructed back to approximately 1600.

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Table 1. Selected long time series in Puget Sound.

Measurement Quantity	Years Sampled	Range of Quantity	Author
1. Lead in sediment from central Puget Sound	1845-1980	5-50 ppm	Crecelius and Curl
2. Sulfite waste liquor near Port Gardner	1955-1985	5-100 PBI	Brown, Maguire, Armstrong, and Duxbury
3. Mid-depth current speed in central Puget Sound	1972-1984	4-12 cm/s	Ebbesmeyer, Coomes Cox, Cannon, and Bretschneider
4. Types of unusual organisms in Puget Sound and Strait of Juan de Fuca	1900-1986	0-6	Mearns
5. Molluscs in central Puget Sound sediments	1963-1986	$0\text{-}300/0.1\ m^2$	Nichols
6. English sole landings from Puget Sound otter trawl fisheries	1948-1987	$0.6\text{-}2.5 \times 10^6$ lbs	Bargmann

CIRCULATION IN PUGET SOUND

A CONVEYOR BELT FOR CONTAMINANTS?

Alyn C. Duxbury,
Washington Sea Grant Program
Session Chair

Introductory Statement

Alyn C. Duxbury*

In marine systems, the movement of water transports soluble and suspended materials. If the net flow of the current as averaged over time has a preferred direction, so too will the advective transport. Some components of currents may be oscillatory and result in a prefered direction only over half their oscillatory cycle, e.g., tidal currents. Soluble and suspended materials may also be transported by turbulent diffusion processes—processes having a non-prefered direction in water motion or turbulence generated by either the oscillatory or net direction currents, but resulting in transport of dissolved material away from an area of high concentration. Both advection and turbulent diffusion transfer soluble or suspended materials from place to place.

Physical transport processes are extremely important in determining the fate of materials, such as pollutants, in the water. It is essential to know how pollutants move, the rates at which they move, and how their movement can affect their distribution in space, the biota and, ultimately, humans. The magnitudes of the water-borne transport fluxes can be very large in comparison to other fluxes, such as those caused by biological, chemical or sedimentation processes. In many cases, contaminant fluxes are estimated by measurements other than direct meansurements of the physical transport processes. Physical transports must be determined accurately in order to measure the fates of pollutants as small changes in large transports often determine what has happend to a pollutant.

Today's speakers will provide an overview of how transport processes are studied. Mathematical models of physical processes that are based on different premises and therefore yield different results and uses will be discussed. Direct observational data will show that transports vary in time and that the variations are related to changes in environmental conditions. Further, direct observations are required to test the applicability of models.

Specific studies will show how and why changes in environmental conditions alter transports. Last but not least, average integrated transports can be hindcasted using budget approaches. All these methods complement each other and are gradually leading the way to analytical techniques that will eventually define a compromise approach to the understanding of water and pollutant transports. This compromise will have the qualities of being solvable with reasonable data requirements and will yield estimates at an accuracy level sufficient to understand the significance of physical transport processes on the well being of Puget Sound. We may never be able to fully describe nature as it actually exists, but we may be able to approximate it sufficiently to understand what controls it.

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A Laterally Averaged Model of Currents in Admiralty Inlet and the Main Basin of Puget Sound

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Introduction

A numerical model capable of describing tidal currents and baroclinic and wind driven circulation in Admiralty Inlet and the main basin of Puget Sound is being developed. The model is a two-dimensional laterally-averaged description because of the long, deep, and narrow character of the system and because a model of reduced dimension permits longer simulations. The model is intended to address the propagation of quasi-fortnightly intrusions of denser oceanic water across the sills in Admiralty Inlet and down the axis of the main basin (Geyer and Cannon, 1982; Bretschneider *et al.*, 1985). It must also describe the substantial variations of tidal currents throughout the Sound (Mofjeld and Larsen, 1984) and the effects on currents of time-variable winds and river discharge. These are the minimum requirements of a model of the Sound that is intended to be useful in along-axis water quality simulations where tidal-time scale motions are important.

Model Description

The model is a primitive equation model that conserves mass, momentum, and salinity (e.g. Hamilton, 1976; Wang and Kravitz, 1980). The turbulence kinetic energy equation is used in defining the time- and space-dependent coefficients for the diffusive exchange of momentum and salt (e.g. Smith and Takhar, 1981). An equation of state, turbulence length scales, and an algorithm for correcting the eddy viscosities and diffusivities for the effects of stratification must also be specified. Boundary conditions required for the solution include specification of the sea-surface height and salinity profiles in time at the entrance, and histories of the distribution of wind stress and of river discharge. The model is solved on a rectangular grid by finite difference. The present realization of the model treats Puget Sound as nine interconnected sub-basins, each represented as a channel of uniform depth and width and having a rectangular cross section. The four sub-basins in the model comprising Admiralty Inlet and the main basin are treated in two dimensions, while the remaining branches (Hood Canal, Whidbey Basin, Colvos Passage, and south Sound) are one-dimensional. The model currently resolves motions at a 3-km scale horizontally and a 10-m scale vertically and is capable of

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economically simulating motions over fortnightly to seasonal time scales.

The model differs from many previously developed laterally-averaged models of estuaries in three ways. First, since Puget Sound is geographically complex, the model must be written to accommodate a network of branched channels. Second, the model must encompass a mechanism that permits and restricts the passage of denser water over the sills in Admiralty Inlet. Since the occurrence, strength, and duration of the intrusions appear to be controlled, in part, by the degree of turbulent mixing occurring in Admiralty Inlet, the model must incorporate time-dependent vertical mixing of momentum and salt. This is accomplished through a turbulence closure scheme that makes the magnitude of the vertical diffusive exchanges dependent on, amongst other factors, the vertical shear of the time varying tidal currents. Third, the model must adequately represent the propagation of the intrusion down the axis of the main basin once the intrusion begins. Propagation of a density front with relatively large advection speed requires a special numerical scheme to deal with the artificially large numerical diffusion usually attendant with such motion. An estuarine model addressing all these aspects simultaneously has not been previously available.

Model results

Model results are now becoming available. Despite the present, coarse characterization of the geometry and bathymetry of the sub-basins, salient features of the currents and circulation of Puget Sound are evident in the model results. Tidal currents with velocities exceeding 1 m/s in Admiralty Inlet result from combined diurnal (K_1) and semi-diurnal (M_2) tidal forcing at the northern entrance to the system. In the deeper, broader sections of the main basin, the same tidal currents together rarely exceed 20 cm/s. At The Narrows the tidal velocities approach 2 m/s. Vertical profiles of the tidal currents, in both magnitude and phase, reflect the effects of bottom drag.

Time sequences of salinities from the model show that higher salinity water does spill over the step at the landward end of Admiralty Inlet and down into the main basin. By following a specific salinity contour in time, a speed for the advancement of the intrusion front can be calculated. The result is a propagation speed of ~20 cm/s; in comparison, Holbrook *et al.* (1983) estimated a range of propagation speeds of 7-15 cm/s based on observations of five intrusions. The near bottom flow created by an intrusion has a speed, in the main basin, comparable to the maximum tidal currents. Thus during periods of intrusions near bottom current speeds are nominally doubled and during those periods resuspension of bottom sediments is much enhanced (Lavelle *et al.*, 1984). The landward flow of the intrusion along the bottom and the enhanced resuspension must favor the southward transport of bottom sediments in the main basin during intrusion intervals.

The conditions for the passage of denser bottom water through Admiralty Inlet are not yet clearly identified from the model, but

it is clear that the occurrence of an intrusion is quite sensitive to the parameterization of mixing in Admiralty Inlet. The buoyancy flux resulting primarily from the discharge of fresher water out of Whidbey Basin is also likely to be seen as a factor. Model results suggest that weakened mixing during neap tides does favor the passage of the denser oceanic water over the sills. Eddy viscosity/diffusivity values of 500 cm^2/s in Admiralty Inlet, on the other hand, prevent denser water from passing into the main basin.

Residual flows computed for one intrusion event show the expected landward bottom flow in the lower half of the water column and the compensating seaward return flow in the upper half. In the main basin these residual flows are largest at the northern end of the main basin and decrease progressively southward indicating a transport from landward bottom layer to seaward surface layer flow over the entire length of the main basin. The seaward residual flow is intensified below the surface at the junction of the main basin with Whidbey Basin as the residual flow passes below the lens of fresher water being discharged from Whidbey Basin.

The landward fluxes of water at any location can be computed by integrating the flow over the cross-sectional area of the lower water column. For a single intrusion, the model suggests a landward flux in Admiralty Inlet of 28×10^3 m^3/s, which may be compared to estimates of Cannon *et al.* (1984) that range from 14-20 $\times 10^3$ m^3/s. The landward flux from the model in the northern end of the main basin is, in comparison, slightly over three times that computed for Admiralty Inlet. This substantial increase in the landward flux of water in the main basin can only be the result of downwelling in the vicinity of the Admiralty Inlet-main basin nexus. Thus during this model intrusion event approximately two-thirds of the water moving seaward in the upper layers of the main basin is refluxed back into the main basin and advected southward in the bottom layer. Recirculation of water back into the main basin as a feature of the longer term circulation in Puget Sound has been addressed by, e.g., Barnes and Ebbesmeyer (1978), Cannon *et al.* (1984), and Cokelet *et al.* (1988).

The results described here can only be regarded as preliminary. Several changes of the model are now being made, including better definition of the geometric and bathymetric features of the basins. This will lead to better characterization of the currents and circulation. The results to date do suggest, however, that some of the essential features of flow in the main basin of the Sound are captured in a laterally averaged-model. This model will provide the advective and diffusive field definitions that are essential for transport models of particulates and contaminants.

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Tidal Circulation Models for Central Puget Sound

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Introduction

An important element in managing Puget Sound water quality is the better understanding of the flow and transport characteristics of the waters in the Sound. The key to resolving the transport of contaminants from industrial and domestic waste treatment facilities, dredge materials disposal practices, and combined sewer overflow is our ability to characterize tidal circulation in sufficiently small spatial scales (less than one kilometer). The physical laws governing such small scale tidal circulation and transport characteristics in Puget Sound are represented by a set of complex mathematical equations which can be solved only with the aid of high speed computers. A computer software which solves such equations describing the tidal circulation is termed a tidal circulation model in this study.

This paper introduces the main features and the application of two tidal circulation models for Central Puget Sound. The two models are formulated differently according to specific assumptions and approximations made of the basic physics of the flow and transport phenomena. Both models have been validated against known conditions and observed field data in Central Puget Sound. The primary goal of this study was to compare and evaluate the two proposed models for further application to Puget Sound water quality management. The results of the comparison of the two models with field data are briefly presented here.

Tidal Circulation Models

The first model considered is a vertically averaged model which assumes the current and density structures at any point in Puget Sound do not change over the water depth. While such an assumption is reasonable for certain portions of the Sound at tidal time scale, it may not be valid for other regions. However, such assumption to the flow physics allows the solution of simpler equations with significantly smaller computing cost than the second and more sophisticated model.

The second model applied is a three-dimensional model which incorporates the changes in current and density structures over a

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water column. Due to computing and data limitations, density variation is not considered in the present application. This second model allows a more detailed characterization of the tidal current regime and transport process in Puget Sound. Because of the more complete formulation, the model requires about three times more computing resources compared to the first model.

Model Implementation

In this initial study, the two models were applied to only Central Puget Sound from Point Wells to the Narrow at Tacoma (Fig. 1). In order to model the flow and transport features within this region, tidal current characteristics at the boundaries (Point Wells and the Narrow) must be given to the model. Tidal current data were derived for this study from the results of a well-calibrated tidal model developed at the Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration (PMEL/NOAA) (Mofjeld, 1987).

The flow features within Central Puget Sound were represented in the models by a uniform 762-meter horizontal grid system, i.e., tidal current and tide were calculated at grid points that are 762 meters apart throughout the Sound. The three-dimensional model resolved the flow system in two variable thickness layers. The model can accept the input of any number of layers if so desired by the user.

Comparison With Field Data

Using the proper boundary conditions, the responses from both models were compared with available field observations (Mofjeld and Larsen, 1984). A typical comparison between model generated and observed M_2 tidal characteristics is shown in Fig. 2. M_2 is a key lunar constituent (influence) in the occurrence of tide in Puget Sound. The amplitude figures shown in Fig. 2 are a measure of tidal height and the phase figures are a measure of the time lag between the occurrence of high tide at the specific locations shown and Greenwich meridian. One degree (°G) of M_2 constituent corresponds to an elapsed time of 2.07 minutes. Similar comparison with the key solar tidal constituent (K_1) are also shown in Fig. 2. The comparison between the observed and computed M_2 current ellipses (which is a composite plot of the magnitude and direction of current at a location) at selected stations are shown in Fig. 3.

Summary of Study Findings

The comparison between the model output and field observation show that the models are fully capable of capturing the main characteristics of the tide and tidal currents in Central Puget Sound. The models do better in reproducing the characteristics of the tide than those of the tidal current. Some of the more pronounced discrepancies in tidal current ellipse comparison are thought to be caused mainly by inadequate spatial resolution at the narrrow channels and passages. A variable or

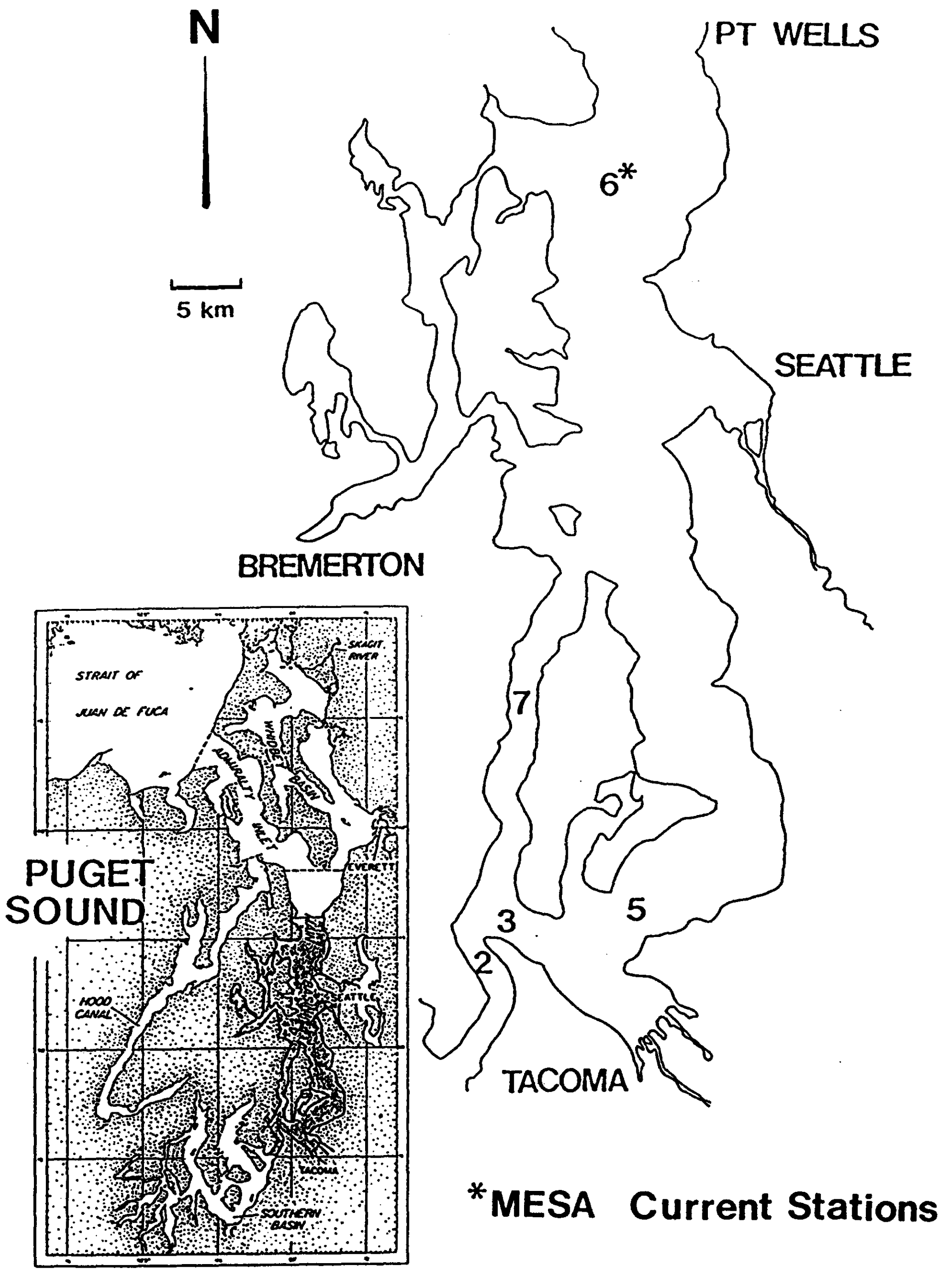

Fig. 1 Central Puget Sound

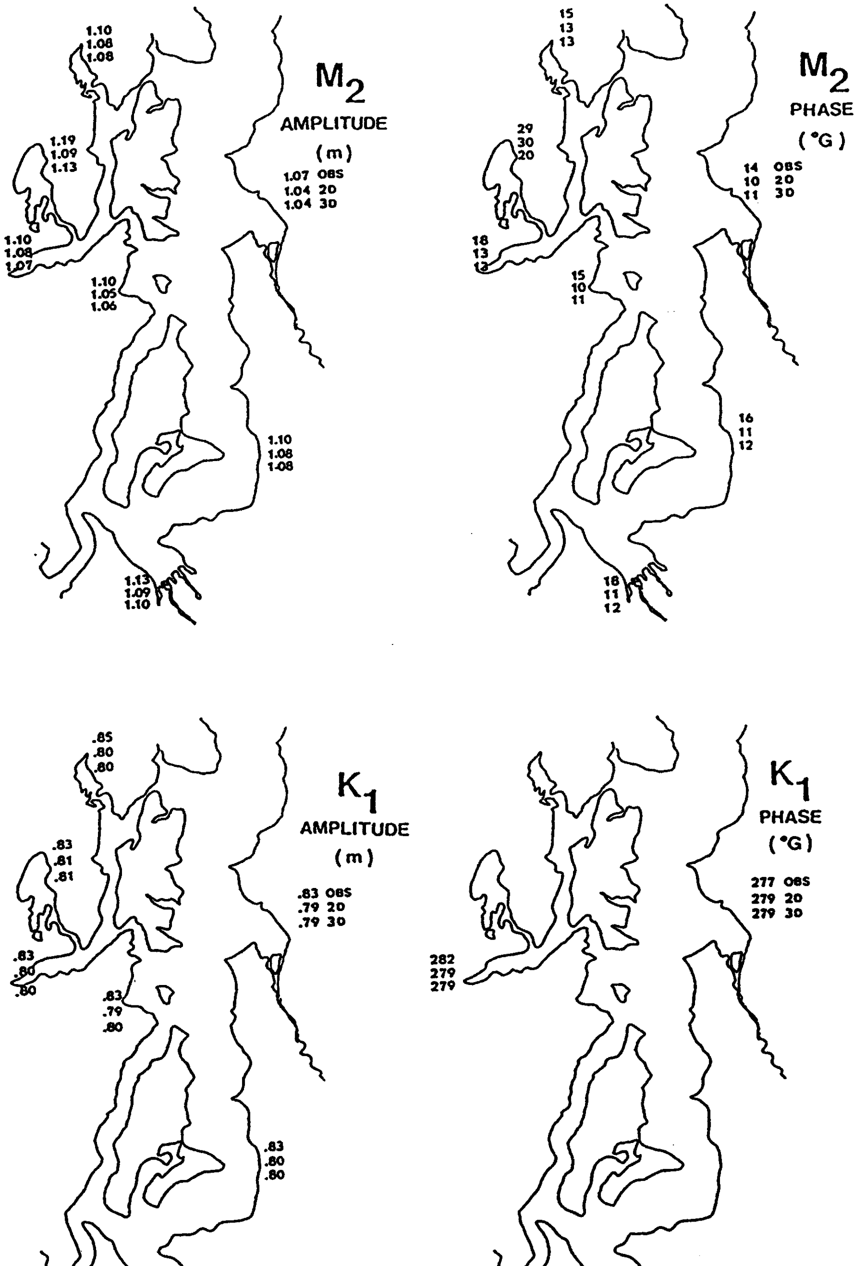

Fig. 2 Comparison of tides. The three figures at each station are respectively observation (Mofjeld and Larsen, 1984), 2D and 3D model calculations.

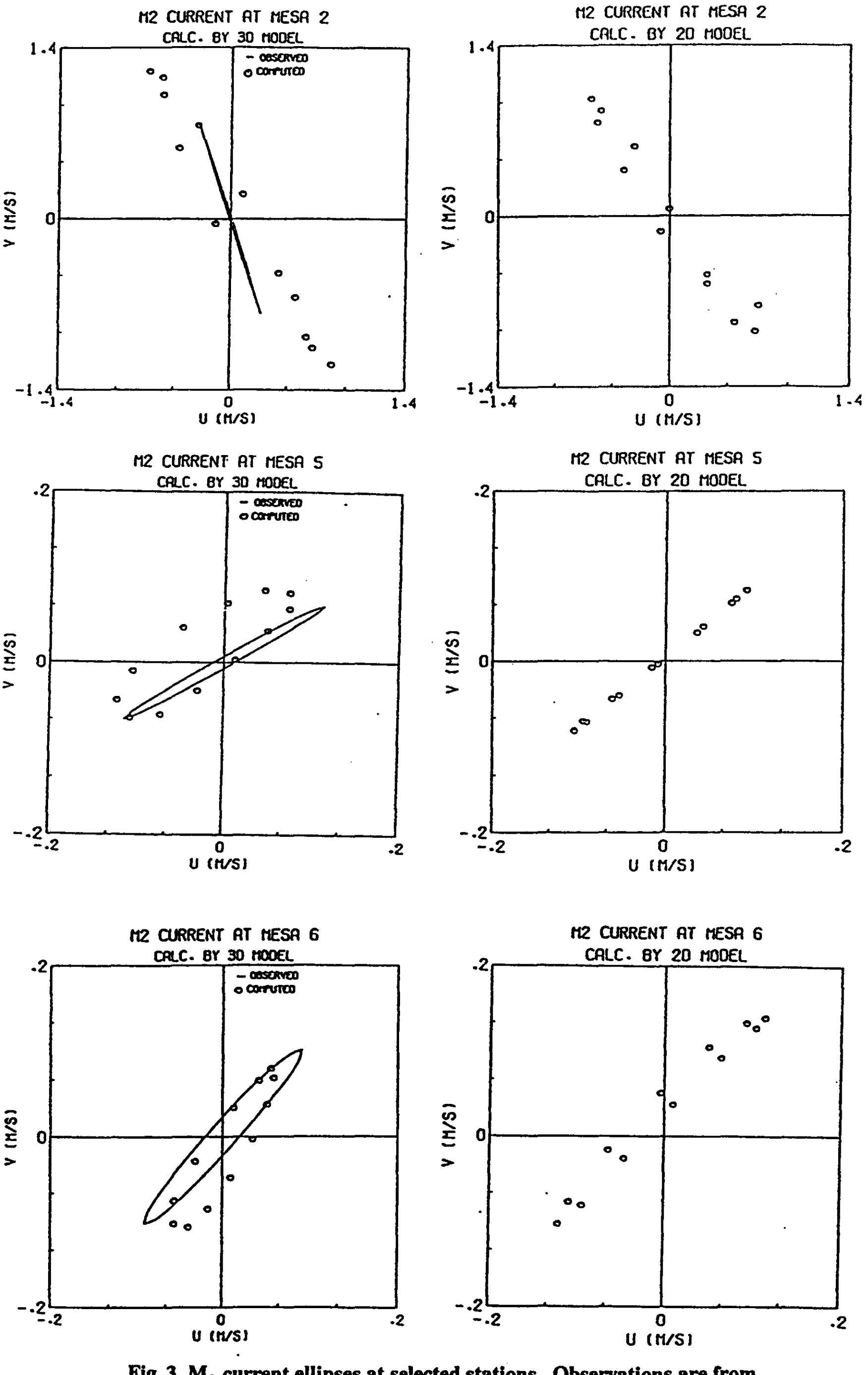

Fig. 3 M_2 current ellipses at selected stations. Observations are from Mofjeld and Larsen (1984).

nested grid resolution for the more detailed calculation of the flow will significantly improve the model results. Such development effort is currently being considered.

The study found that the three-dimensional model results are in better agreement with the field data. This is due to the model's ability to better represent the physical features in Puget Sound. The three-dimensional model however requires about three times more computing resources to run.

At the present grid resolution, the two-dimensional model can be used as an effective tool to estimate basin wide transport and flushing characteristics. Some examples of such application will be presented at the meeting. For certain engineering and planning solutions requiring more detailed knowledge of the current and tide (e.g. outfall siting, dredge material disposal site selection, contaminant transport in urban bays, etc), the use of the three-dimensional model (or equivalent) at much smaller spatial resolution scale is recommended.

Acknowledgement

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Seasonal and Interannual Variations of Tidal Mixing and Excursions in Admiralty Inlet

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Introduction

The Main Basin of Puget Sound is often considered a better location for effluent disposal than poorly flushed areas like Elliott and Commencement Bays because it has strong tidal dispersion and a vigorous estuarine circulation. After leaving outfalls or more distributed sources, contaminants take a variety of pathways. Many contaminants such as lead and polyaromatic hydrocarbons are in the form of particles that sink to the bottom. After being resuspended and transported by fluctuating currents, these particles are eventually buried in the bottom by the natural deposition of clean sediment.

Other contaminated particles are buoyant and tend to rise toward the water surface where they are carried to shore or transported elsewhere in the Sound by wind-driven and other currents. The regional distributions of particle-borne as well as dissolved contaminants are therefore due in part to the currents in the Main Basin along with the source distributions and the chemical, biological and sediment dynamics of the contaminants.

A major contribution to the vigorous circulation in the Main Basin is the frequent influx of relatively dense water from Admiralty Inlet that sinks to the bottom layer of the Main Basin (Geyer and Cannon, 1982; Cannon, 1983). These density intrusions move southward in the deeper reaches of the Main Basin and create a compensating northward current of less dense water in layers nearer the water surface. Combining with the flood tidal currents, the intrusions resuspend and transport sediment toward the south and displace resident near-bottom water that may have accumulated particle-borne and dissolved contaminants.

The observed occurence and character of the density intrusions vary with the seasons of the year. This is caused in part to the seasonal variations in the flow of fresh water from the land surrounding Puget Sound, to the variations in the density of source water outside Puget Sound in the Eastern Strait of Juan de Fuca and possibly to the seasonal progression of the winds in the region (Ebbesmeyer and Barnes, 1980; Cannon, 1983).

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Also contributing strongly to the seasonal variations of the density intrusions are variations in tidal processes within Admiralty Inlet. One process is the mixing of water types by tidally-generated turbulence (Geyer and Cannon, 1982). Low tidal mixing allows dense source water to flow into the Main Basin without substantial dilution by less dense water flowing northward into Admiralty Inlet from the Main Basin. A second process is the tidal excursion that can carry water from the northern source region into the Main Basin within a single tidal cycle (Rattray and Lincoln, 1955). Both these tidal processes also vary over interannual time scales.

In the discussion that follows, we shall explore the seasonal and interannual variations of the tidal mixing and excursions in Admiralty Inlet using predictions that are based on observed tidal currents.

Tidal Mixing and Excursions

Shown in Figure 1 are predicted tidal currents and excursions based on observed currents at a station MESA 10 located mid-channel off Bush Point in Admiralty Inlet (Mofjeld and Larsen, 1984). The predictions are for a three-week period beginning in mid-March, 1988, and show a typical period of relatively low tidal current and excursions that often occurs during the spring and fall.

Also shown in Figure 1 is a mixing index that increases with decreasing tidal mixing in Admiralty Inlet. The index is based on an estuarine Richardson number (Fischer, 1972) with peaks during periods of low tidal current speeds. It is a very sensitive function of the tidal currents because it is proportional to the reciprocal of the cubed tidal current speed.

The period of low tidal mixing (Figure 1) is also a period of small tidal excursions. However, during the latter half of the period the excursions do penetrate farther south toward the Main Basin. Also, in the first half of the period the southward excursions dwell in time which would allow more time for dense water to spill over the landward sill of Admiralty Inlet into the Main Basin. A comparison of the mixing index with near-bottom observations in the Main Basin (Geyer and Cannon, 1982; Cannon, 1983) indicates low tidal mixing dominates the occurence of intrusions into the Main Basin. Still, tidal excursions probably play an important secondary role.

Seasonal and Interannual Variations

Multi-year time series of the mixing index computed for 1970-1989 indicate that in a typical year periods of lowest tidal mixing in Admiralty Inlet occur preferentially at two-week or monthly intervals during late winter and early spring and during late summer and early fall, especially near the equinoxes. Long periods of high tidal mixing can occur during late spring and early summer as well as late fall and early winter near the solstices. Every fourth or fifth year is anomalous with relatively high tidal mixing

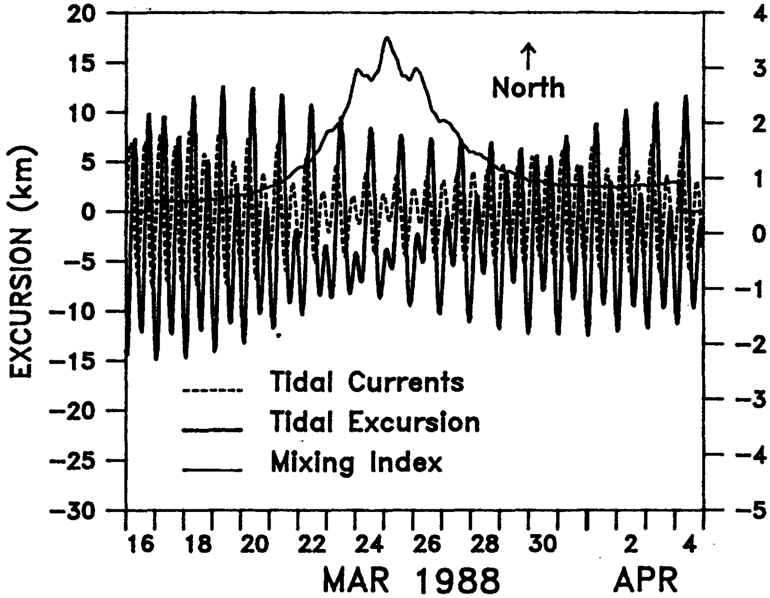

Figure 1. Predicted tidal currents and excursions based on observed currents at a station in Admiralty Inlet. Also shown is a mixing index that increases with decreasing tidal mixing.

and no definite seasonal pattern. Time series of tidal excursions show opposite though less intense variations in strength with largest excursions during solstical tides.

While there is often a strong relationship with low tidal mixing and the occurence of density intrusions into the Main Basin, exceptions are often found such as observed intrusions during solstical tides. This indicates that other factors like tidal excursions, density contrasts between the Main Basin and the Strait of Juan de Fuca and wind forcing must also be considered to fully understand and predict the occurence and character of intrusions.

Acknowledgments

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Flow Variations through Sections across Puget Sound

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Abstract

Flow in the Puget Sound estuarine system is important in determining the fate of contaminants within the system. Research since the early 1970's has focused on determining circulation characteristics, space and time variations, and the dominant physical processes causing these variations. During the course of this research some of our earlier ideas have changed, and this paper presents a brief overview of our present understanding of the dominant physical processes affecting the Puget Sound system.

Cross-channel observations of currents recently made at a few locations suggest residual fluxes about half those estimated earlier from midchannel observations. Variations in the residual circulation (tides removed) are dominated by two physical processes. Wind effects account for about 50% of the residual energy, and density driven deep-water intrusions account for about 20%. The winds appear to have effects both near the surface and at middepths. Previous studies have shown that major bottom-water inflow events occur during neap tides when mixing over the sill is least and propagate along the main basin and into some side basins. New observations show the onset also may be the result of salinity variations across the sill caused by changes in the Strait of Juan de Fuca estuary which in turn may be partly caused by coastal storms.

Introduction

Fjords are estuaries which have resulted from glacial erosion and which generally occur at higher latitudes. Typically, they are relatively long and deep and possess one or more sills. The oceanography of fjords has been studied extensively in Scandinavia and on the west coast of North America. Much of the early work was descriptive covering a wide variety of fjords. More recently, a broad range of time variations in currents has been elucidated which must be considered when studying particular kinds of processes.

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Puget Sound is a fjord-like estuarine system connecting through Admiralty Inlet to the Strait of Juan de Fuca and thence westward to the Pacific Ocean. It is the southernmost glacially carved waterway in western North America. The main basin off Seattle exceeds 200 m depth and is about 60 km long. It is bounded by a broad entrance sill region which extends about 31 km along Admiralty Inlet (actually a double sill, shallowest at 64 m) and by a landward sill in The Narrows (44 m) connecting to the southern basin. Studies have focused on quantifying spatial and temporal variations in circulation and transport in this kind of estuary, which actually is a set of of smaller estuaries with widely varying characteristics (Cannon, 1983). This paper focuses on the main basin which connects the Strait of Juan de Fuca with smaller embayments (e.g., Elliott and Commencement Bays; Baker *et al.*, 1983).

Flow Characteristics

Flow in the estuary is tidal with a superimposed time-varying gravitational circulation. Vigorous vertical mixing of water occurs in the sill zones. Amplitudes of the tidal currents in the deep basin are about half as large as those on Admiralty sill, and there is not always a discernible tidal component in salinity. Flow in Saratoga Passage is even weaker. The larger net flows and higher salinities over Admiralty sill generally occur during neap tides, and these become bottom water intrusions in the deep basin. These intrusions propagate throughout the system, into Port Susan and to the Narrows. Their extent into Hood Canal and the southern basin is not known.

When the tides are filtered from the observations, the net flow in most of the estuary is seaward near the surface and landward near the bottom. In the northern half of the main basin, the change from inflow to outflow occurs at about 50 m in a depth of 200 m, or 25% of the total depth. This is intermediate between the deeper level of 40-50% for partially mixed estuaries (shown here in Admiralty Inlet) and the shallower level of 10-15% for more classical fjords with major freshwater inflow upstream (shown here in Saratoga Passage). Hood Canal currents are weaker and more variable because there is no major source of freshwater. The net flow in most of the estuary is two-layered. An exception to two-layered flow occurs in the southern part of the main basin where geometry has a significant effect. In East Passage the net flow at all depths, except for a very thin surface layer, is southward. In Colvos Passage residual flow is northward at all depths due to the tidal circulation around Vashon Island caused, in part, by the strong northward ebb out of the Narrows.

Salinity sections along channel show strong horizontal stratification through Admiralty Inlet similar to some coastal plain estuaries, while that in the deeper basin shows a relatively weaker horizontal stratification more characteristics of fjords Saratoga Passage also includes a pronounced thin, low-salinity surface layer. The Duwamish River has characteristics of salt-

wedge estuaries with a sharp halocline and upper and lower uniform salinity layers.

Cross-channel observations have been made at only a few locations (Bretschneider *et al.*, 1985). In Admiralty Inlet off Bush Point (Oct-Nov 1977) the depth of change from net inflow to outflow decreases from east to west. Currents in East Passage (Mar-Apr 1985) both at Three Tree Point and at Dash Point show shallow seaward flowing (northward) layers overlying deeper landward flowing (southward) layers extending to the bottom. A core of maximum velocity is evident at mid-depth, and there is a strong near-surface vertical current shear. The section off Meadow Point in the main basin (Apr-July 1985) shows a well-defined two layer current regime separated by a layer of no-net-motion which varies in depth from 55 to 75 m across channel. A relatively strong horizontal core of seaward flow is evident between 10 and 30 m part way across the section centered on the western side. On the east side of the channel, the nearshore surface flow is reversed from the normal estuarine flow, probably due to eddy circulation around West Point. A slanting band of maximum landward flow is seen in the lower layer extending from 90 m to the bottom. Significant cross-channel variations of subtidal current flow are evident at all sections, and important features of the flow field would have been missed if only the center mooring had been used.

Estimates of the flux of water have concentrated on the lower layer of inward flow, partly because observations rarely were extended to the surface because of shipping. The upper layer, or seaward flow, must be equal in flow to the lower layer plus the relatively smaller amount of freshwater being transported seaward. The first estimate for the average southward flux in the main basin from direct measurements off Meadow Point was 4.3×10^4 m^3/sec using mid-channel month-long average currents (assumed uniform across channel) for winter 1973. Daily average transports, however, ranged from 2 to 8×10^4 m^3/sec. Inflow midway over the Admiralty Inlet sill off Bush Point was calculated from a three-station cross section at 2.1×10^4 m^3/sec, less than the estimate off Seattle and supporting a refluxing concept that 1/2-2/3 of the seaward flowing water was entrained into the bottom inflowing water. The recent current measurements across three cross sections in the main basin indicate more uniform flow throughout the system and on the sill. The average inflows from south to north in each of the sections are respectively 2.1, 2.3, and 1.9×10^4 m^3/sec. Thus, it is possible that no major refluxing occurs at the sill, except by entrainment during specific intrusions of bottom water discussed below. Reducing the estimated flux from 4.3 to 2.1×10^4 m^3/sec implies a doubling of the time required to replace water below sill depth in the main basin, previously estimated by Cannon and Ebbesmeyer (1978) as two weeks.

The transport of water along the Sound is different than that in coastal plain estuaries which increases going down the estuary due to entrainment from the lower layer into the upper layer. However, the observations for the Sound are from different seasons. Recent calculations using a simple two-layered box model of the Sound

predicted a seasonal change in flux with an average transport of about 3.0×10^4 m^3/sec for winter conditions and about 1.4×10^4 m^3/sec for autumn (Hamilton *et al.*, 1984). Observations are insufficient to detect a seasonal change. Considerable flux variations also exist on shorter time scales as was noted above for the main basin. Over the sill variations occur depending whether there is a specific inflow event (Cannon *et al.*, 1984). The average inflow over a two-month interval was about 2×10^4 m^3/sec. However, the average inflow during the event on 14-20 February was 3.5×10^4 m^3/sec and during the subsequent low inflow on 21-27 February was 0.13×10^4 m^3/sec. For comparison, the average fluxes in the Strait of Juan de Fuca about midway to the ocean are about 5-10 times larger, varying between 10-20×10^4 m^3/sec (Cannon and Bretschneider, 1986).

Physical Processes

The cross-channel observations in the main basin at Meadow Point and Three Tree Point also have been subjected to analyses which can reveal the dominant modes of the variations in the circulation (Bretschneider *et al.*, 1985; Cannon *et al.*, in progress). Both sections show the largest variance of the non-tidal currents is caused by the winds and account for about 50% of the remaining variance. The second largest are caused by bottom water intrusions and account for about 20% of the variability. A third mode, evident only on the southern section, accounts for about 15% of the variance, and clearly demonstrates the partial recirculation around Vashon Island. The major effects of this flow occur above 100 m, the approximate depth of Colvos Passage, with the peak at about 50 m. There is an approximately 100% agreement between the time series of this characteristic in East Passage and independently measured currents in Colvos Passage.

Wind effects, the dominant mode of variation, occur over time intervals of hours to a few days. The predominant winds are from south to north along the Sound with occasional reversals between storms and during summer high pressure systems. Studies of wind effects have been limited due to the difficulty of maintaining near-surface instrumentation because of shipping traffic. However, there is some evidence that changes in this north-south pattern are accompanied by large vertical changes in the depth between the inflowing and outflowing mean currents. The previously described modal analysis showed a mid-depth compensating flow at 100 m during surface flows. More detailed studies of these processes are underway and being planned.

Changes in flow and salinity during intrusions, the second dominant mode, occur approximately at fortnightly intervals, but not every fortnight. During neap tides, tidal currents on the sill are relatively weak, there is less vertical mixing, stratification increases, and a gravitational circulation intensifies in the bottom layer (Geyer and Cannon, 1982). This results in relatively undiluted water from outside Admiralty Inlet being able to transit the sill resulting in density currents which flow into the bottom of Puget Sound and propagate up estuary displacing existing bottom

water. This renewal of bottom water is characterized by a rapid change in temperature followed by a 2-10 day up-estuary pulse of deep currents and maxima in salinity and density. This deep intruding water spreads with a constant mean velocity of 7-14 cm/sec and a density difference that varies inversely with distance due to entrainment (Holbrook *et al.*, in progress). The internal readjustments in flow due to the intrusions occur in the surface layer over the sill, but are at mid level below sill depth in the fjord.

Prediction of the onset of intrusions is of major importance because they do not occur at every fortnight. Recent observations indicate that the horizontal pressure gradient across the sill may also affect the intrusions (Cannon *et al.*, in progress). The onset of several major intrusions occurred before minimum neap tidal currents and after the difference in salinity (density) between inside and outside the sill reached some nominal value. Salinity variations in the Strait of Juan de Fuca were larger than in Puget Sound, and some of the difference appeared related to coastal storms.

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The Annual Mean Transport and Refluxing in Puget Sound

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Introduction

Where will substances go after being introduced into Puget Sound? How long will it take to get there? What will their concentration be? These questions can be answered in part by understanding and predicting the flow of water. Its movement is controlled by the wind, by the ebb and flow of the tide, by river inflow, and by deep intrusions of salt water from the sea.

Puget Sound consists of a series of deep, stratified reaches (Figure 1) separated by junctions and shallower sills where most of the rivers enter and the mixing between water types occurs. When the effects of the wind and tide are averaged over a time period of one year or more the flow in each reach is two-layered with denser salty water flowing landward in the deep layer and fresher water flowing seaward near the surface. At the junctions and sills these flows intermingle in turbulent mixing zones where the flow from any incoming layer can be split into two parts: an efflux fraction which continues on into the next reach and a reflux fraction which recirculates into its original reach (Figure 2).

Fresh Water and Salt as Tracers

Fresh water and salt are two natural tracers which behave conservatively in Puget Sound, i.e. they act passively and have no sinks within the estuary. Their sources - the rivers and the ocean - are distinct, well-defined and measurable. Furthermore a five-year-long

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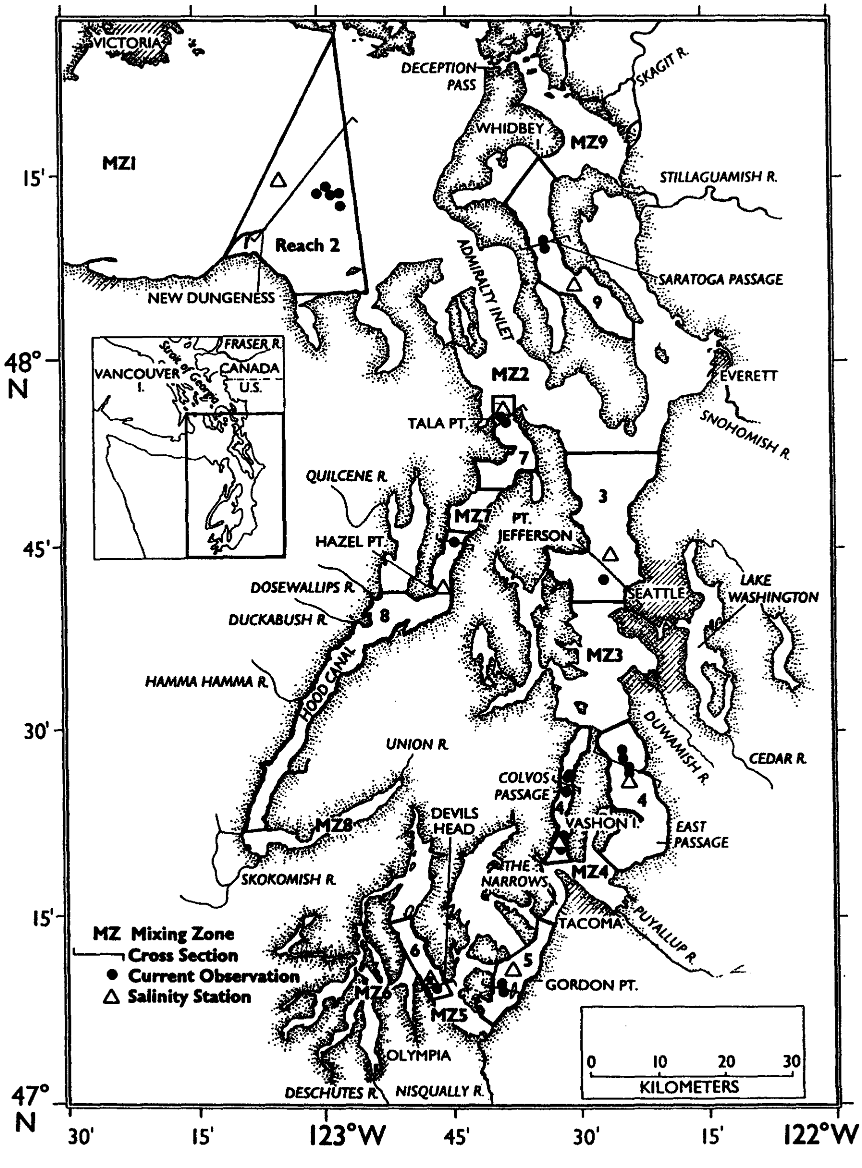

Figure 1. The reaches and mixing zones of the Strait of Juan de Fuca/Puget Sound system. Reach 1 (not shown) is at the entrance to the Strait. (Figure 1b of Cokelet *et al*, 1987)

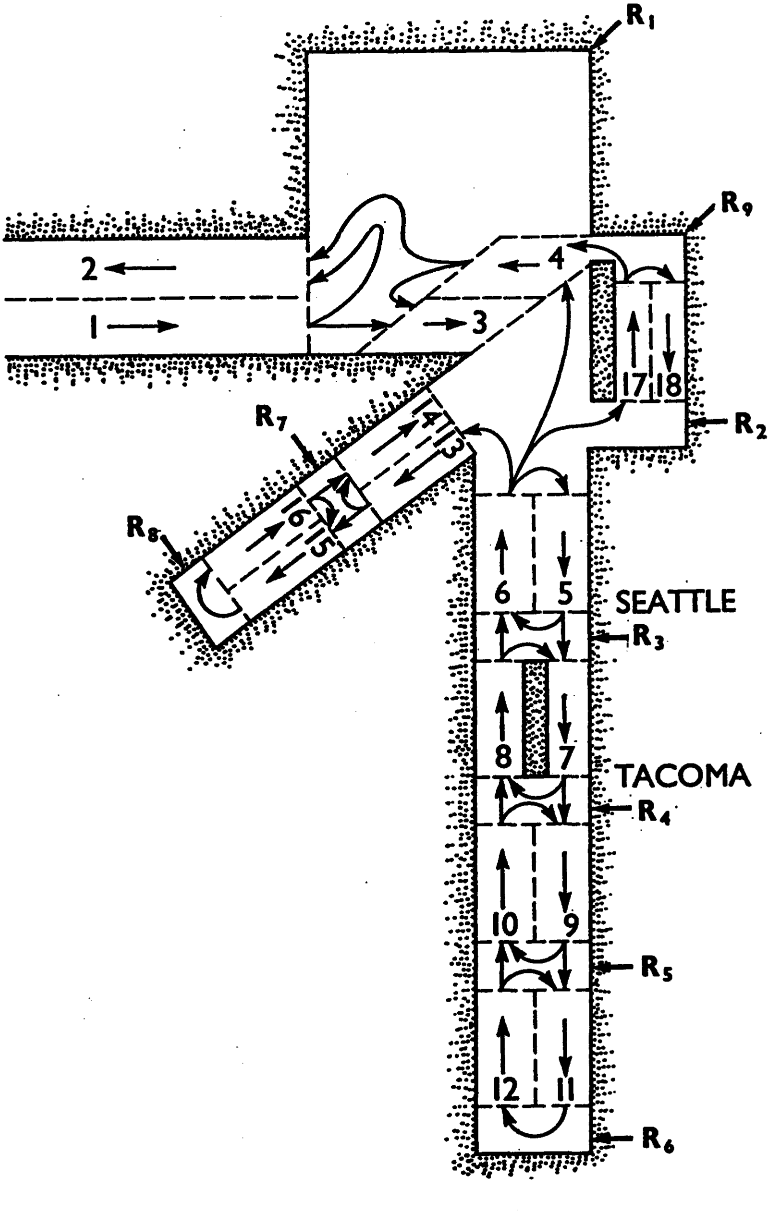

Figure 2. A schematic diagram of the refluxing model. The efflux/reflux coefficients are represented by arrows in the mixing zones. In reality the landward- and seaward-flowing layers are superposed except around Vashon Island where they are juxtaposed.

time series of salinities sampled every six weeks from the Strait of Juan de Fuca to southern Puget Sound including Hood Canal and Saratoga Passage has been collected by Barnes and Collias (1954a-c, 1956a-c) from 1951 through 1955.

Cokelet and Stewart (1985) have expressed the efflux/reflux fractions as coefficients in the equations governing the conservation of mass. The coefficients are calculated from the salinities after appropriate averaging and weighting by the strengths of the observed currents.

Ideally the currents should be measured in cross-channel arrays within each reach at the same time as the salinities. Unfortunately this has not been possible in Puget Sound. The best temporal and areal coverage of salinity observations stems from the early 1950's, but practically no currents were measured then due to instrument limitations. These limitations were overcome in the 1960's, and several current observations exist from the 1970's and 1980's (Cox *et al*, 1984). However no simultaneous measurements were performed in all of the Puget Sound reaches. Cokelet *et al* (1987) have recently constructed composite current profiles for each reach and combined these with the older salinity observations to produce time series of flux-weighted salinities appropriate for the efflux/reflux theory.

Figure 3 (Cokelet *et al*, 1987) shows the upper and lower layer flux-weighted salinities for each Puget Sound reach. These are time series of one-year moving averages. The effects of the seasons are smoothed out, and the difference between years becomes noticeable. In particular Figure 3b shows the cyclic nature of the salinity in the main basin and the southern Sound. This sinuous behavior is linked to the runoff and the salinity of the deep incoming oceanic layer off Pillar Point in the Strait of Juan de Fuca.

As one moves landward from the Strait to the southern Sound off Devils Head, the landward-flowing, usually lower-layer salinities steadily decrease due to dilution with fresh water. However in the seaward-flowing upper layers this pattern is interrupted in Colvos Passage which is quite a bit saltier than the surface layer just seaward off Point Jefferson.

Transport

Time series of the one-year moving average volume transports (Figure 4) have been inferred from the fresh water and salt distributions by Cokelet *et al* (1987). This is the first time that the annual transports in the principal reaches of the Strait and the Sound have been determined

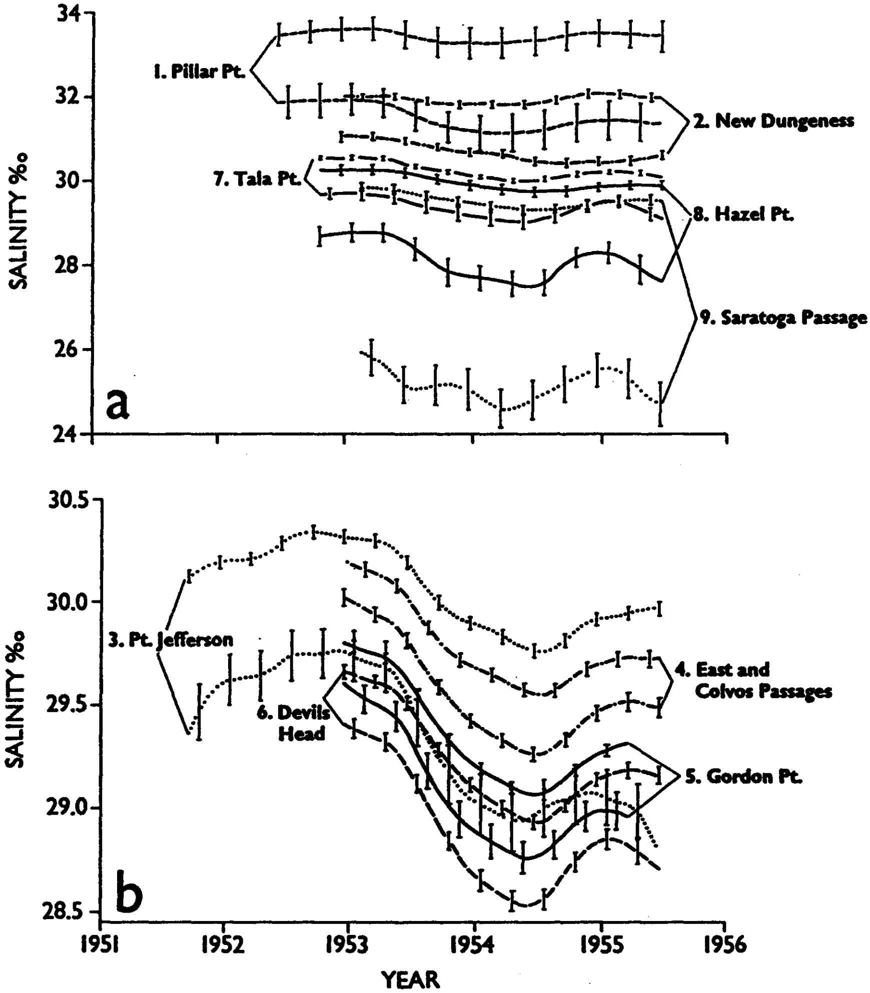

Figure 3. Time series of the annual mean flux-weighted salinities. (Figure 8 of Cokelet *et al*, 1987)

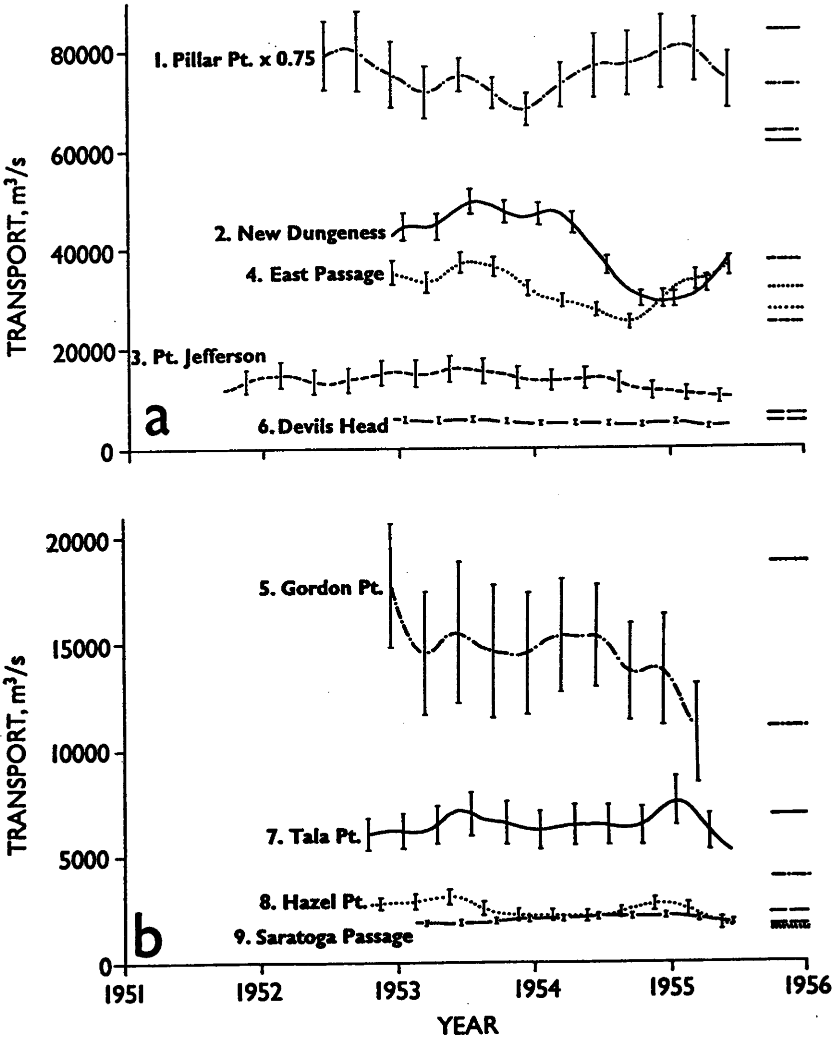

Figure 4. Time series of the annual mean volume transports inferred from conservation of fresh water and salt. (Figure 9 of Cokelet *et al*, 1987)

simultaneously, over several years and with error estimates. With few exceptions they agree well with estimates derived from scattered, shorter duration current observations and from oxygen utilization techniques.

The transport off Point Jefferson ranges between 9000 and 19,000 m^3/s which is substantially lower than the 42,000 to 43,000 m^3/s inferred from month-long deployments of a single current meter mooring by Cannon & Ebbesmeyer (1978) in the winters of 1972 and 1973. Both estimates could be in error for a variety of reasons. One candidate is that the midchannel current is not representative of the cross-channel mean since the channel cross section changes drastically at this site. Later estimates (Ebbesmeyer *et al*, 1984) using composite cross-channel arrays of moorings are 20,000 to 22,000 m^3/s which is nearer to but somewhat higher than our range.

The pattern of the volume transports is interrupted in the same way as the seaward-flowing salinity pattern. The transports decrease (Figure 4) as one moves landward from Pillar Point but suddenly increase in East and Colvos Passages (Colvos is not shown but nearly coincides with East at this scale) before decreasing again off Gordon Point and Devils Head. In order for the transport around Vashon Island to be double that of the reaches just to landward and to seaward requires substantial recirculation.

<u>Reflux Coefficients</u>

The reflux coefficient from Colvos to East Passage at the north end of Vashon Island averages 0.51, and from East to Colvos Passage at the south end it is 0.69. These values and the remaining results are based upon the grand mean flux-weighted salinities of Figure 3 taken over the period 1953 to mid 1955 for which simultaneous data are available for each of the nine reaches.

Cokelet and Stewart (1985) have shown that two tracers alone - fresh water and salt - are not sufficient to determine fully the efflux/reflux coefficients for a mixing zone where two reaches and a river meet as in most Puget Sound applications. Similarly two tracers are insufficient at a multiple junction such as Admiralty Inlet. A maximum entropy method (Cokelet and Stewart, 1985) has been used to resolve the uncertainty and to produce the solution which is maximally noncommittal with regard to the missing tracer information.

Ebbesmeyer and Barnes (1980) calculated that about 2/3 of the water flowing seaward off Point Jefferson is refluxed landward into the lower

layer at Admiralty Inlet. The present calculations put this reflux coefficient at 0.27 which is considerably lower. The first estimate lacked a complete mathematical theory and a long-term salinity data set properly weighted by the current profile. Also the transport off Point Jefferson was probably too large as noted earlier. The smaller reflux coefficient means that the principal recirculation in the main basin is around Vashon Island.

Tracer Concentrations

The efflux/reflux formulation of Cokelet and Stewart (1985) provides a way to predict the concentration of a conservative tracer injected anywhere within the eighteen layers of the Puget Sound system. Table 1 compares the predicted concentrations measured in parts per billion (ppb) due to an injection of 1 kg/s of a tracer into either the lower or upper layer off Point Jefferson, East Passage or Colvos Passage. Notice

Table 1. The Tracer Concentration in ppb Versus the Point of Injection of 1 kg/s of Tracer.

Layer	Layer 5 Injection	Layer 6 Injection	Layer 7 Injection	Layer 8 Injection
1 Pillar Pt. Lower	0	0	0	0
2 Pillar Pt. Upper	9	9	9	9
3 New Dungeness Lower	9	9	9	9
4 New Dungeness Upper	33	33	33	33
5 Pt. Jefferson Lower	102	38	38	38
6 Pt. Jefferson Upper	100	100	100	100
7 East Passage	101	38	103	71
8 Colvos Passage	100	37	102	102
9 Gordon Pt. Lower	100	37	102	70
10 Gordon Pt. Upper	99	37	101	69
11 Devils Head Lower	99	37	101	70
12 Devils Head Upper	98	37	100	69
13 Tala Pt. Lower	38	38	38	38
14 Tala Pt. Upper	37	37	37	37
15 Hazel Pt. Lower	37	37	37	37
16 Hazel Pt. Upper	35	35	35	35
17 Saratoga Passage Lower	38	38	38	38
18 Saratoga Passage Upper	33	33	33	33

that in the Strait of Juan de Fuca (layers 1 to 4), Hood Canal (layers 13 to 16) and Saratoga Passage (layers 17 to 18) the concentrations are not affected by where in the main basin the tracer is injected. In this sense

these sites are all 'downstream' of the injection point and are unaffected by various 'upstream' injection strategies. However the concentrations in layers 5 to 12 are affected. When the tracer is injected into the seaward-flowing surface layer off Point Jefferson (layer 6) the concentrations in the rest of the main basin (layers 5, 7 and 8) are less than 38 ppb since most of it is carried out to sea with little recirculation. However when injection takes place in the lower layer (5) the tracer is carried landward into the southern Sound, and it recirculates around Vashon Island creating concentrations of about 100 ppb or three times their former value. East Passage (layer 7) injection gives similar values. Injections into seaward-flowing Colvos Passage (layer 8) produce concentrations (70 ppb) midway between those into the surface and bottom layers off Point Jefferson.

Tracer Ages

The mean age of a tracer injected at one site and observed at another can be predicted from the efflux/reflux formulation (Cokelet and Stewart, 1985). This is the average over all paths and particles of the time it takes to get from the point of injection to the point of observation. First it is necessary to calculate the time a tracer spends transiting each individual layer. This is the ratio of the layer volume to its volume flux and is shown in column 3 of Table 2. It varies between 1 day for Colvos Passage to 49 days for the slow fjord-like bottom flow in Hood Canal. These transit times and ensuing ages are lower limits in the sense that the time which tracer particles spend in the mixing zones is neglected.

An example of the mean tracer age is the age of salt particles in Puget Sound. At their source in layer 1 off the Strait of Juan de Fuca's Pillar Point their age is zero by definition. Column 4 of Table 2 lists their ages in the various layers. When the salt leaves the system in layer 2 its mean age is 41 days. That is because most of the salt simply flows into the Strait, is entrained into the surface layer, and flows out to sea again. The salt which is found in the main basin (layers 5 to 8) is more than twice as old, but the oldest salt particles of all are in Hood Canal's upper layer off Hazel Point where their age at the seaward end is 125 days.

Another useful quantity is the lifespan of tracer particles which is the average time it takes to get from their point of injection to the oceanic outlet of layer 2. The lifespan which is a function of the injection point is shown in column 5 of Table 2. Salt particles originating in layer 1 have an average lifespan of 41 days, but much older ones can be found in the population. Tracers injected into the main basin (layers 5 to 8) have mean lifespans of 59 to 90 days, and those injected into the southern Sound (layers 9 to 12) will remain in the entire system from 73 to 78

Table 2. Time Scales in Days for Puget Sound

	Layer	Layer Transit Time	Salt Age	Tracer Lifespan
1	Pillar Pt. Lower	16	16	41
2	Pillar Pt. Upper	14	41	14
3	New Dungeness Lower	5	31	53
4	New Dungeness Upper	3	55	28
5	Pt. Jefferson Lower	13	69	90
6	Pt. Jefferson Upper	7	93	60
7	East Passage	6	84	78
8	Colvos Passage	1	87	70
9	Gordon Pt. Lower	1	88	76
10	Gordon Pt. Upper	1	90	73
11	Devils Head Lower	2	90	79
12	Devils Head Upper	3	93	77
13	Tala Pt. Lower	4	60	81
14	Tala Pt. Upper	2	84	55
15	Hazel Pt. Lower	49	117	121
16	Hazel Pt. Upper	8	125	72
17	Saratoga Passage Lower	41	98	97
18	Saratoga Passage Upper	10	108	71

days on average. The greatest lifespan (121 days) is for particles injected into the deep layers off Hazel Point in Hood Canal.

Conclusion

We have shown where in Puget Sound tracers will be carried, what their concentrations will be as a function of their injection site, how long they will take to get there, and how long they will remain in the system. These predictions are based upon the grand mean of the annual mean circulation over a few years.

Some things need to be accomplished before this work is complete. Time series of the predicted quantities must be calculated using the salinity and transport time series of Figures 3 and 4 to determine their sensitivity to natural environmental variations. Errors in the concentration and age estimates must be assessed. The predicted tracer ages are on the order of a few months, but the circulation model used to predict them is based on annual means. Clearly there is a mismatch in

time scales. Seasonal variations in the circulation need to be incorporated.

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Mixing Processes in Puget Sound:
Modeling Implications

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Management of water quality of and pollutant discharges into a large, multi-basin estuary such as Puget Sound almost inevitably requires use of numerical models. Perhaps the single greatest difficulty in constructing detailed numerical models is correct representation of the various vertical mixing processes that are important at various times and places. This difficulty arises, because these mixing processes are still incompletely understood, and because model predictions are very sensitive to the distribution and strength of vertical mixing. What is known (or not known) about mixing processes in a body of water should, therefore, have a substantial effect on the modeling strategy employed to address both scientific and management questions. This paper consists largely of a simple discussion of the primary vertical exchange mechanisms in large estuaries, with brief indications how or if these processes may be incorporated into numerical models, and, where possible, comments on their relative importance. Implications for modeling investigation design are discussed at the end.

Vertical Mixing Processes

Vertical exchange of momentum and salt between vertically adjacent layers of water is typically responsible both for most of the energy loss to friction and the mixing of salt and freshwater in estuaries. Vertical mixing is inhibited by stable stratification (vertical density differences in which light water lies over heavy water) so that layers of water may slide over on another easily with large velocity differences (shears). A flow where vertical temperature and salinity differences are either absent or more or less compensate one another mixes far more easily and is more frictional. Vertical mixing processes are classified below as either external (originating at the top or bottom boundary) or internal (Gardner *et al.*, 1980). Molecular viscosity does appear in the following list, because it is unimportant at the scales used in numerical models. To be sure, kinetic energy is ultimately lost to viscosity, but

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it is first lost from the tidal flow to intermediate scale mixing processes. The parameterization of these processes implicitly includes the ultimate loss to viscous dissipation.

External mixing mechanisms

Estuarine flows are typically much wider than they are deep, so the main frictional energy loss in most estuaries including Puget Sound occurs at the seabed, not the sidewalls. This energy loss occurs within a turbulent layer (the bottom boundary layer) with enhanced shear (vertical velocity differences). Strong winds add momentum at the surface of an estuary and create a similar turbulent boundary layer near the surface. Stratification reduces vertical turbulent exchange, because mixing dense water with lighter overlying water requires energy -- tidal flow kinetic energy is converted first to turbulence and thence to potential energy (energy of position) by mixing. Turbulent boundary layers occur throughout Puget Sound and are typically a few tens of meters thick. They can encompass the entire water column in shallow areas with strong currents (e.g. over sills), but may be limited by stratification and/or low velocities to a small part of the water column in deep basins. Turbulent mixing is strongest at the times of peak flood and ebb currents, but often decays around slack waters. Thus, external mixing may be replaced as the dominant mixing mechanism by internal mixing during some part of the tidal cycle. This is believed to be an important process governing salinity intrusion in partially-mixed estuaries (Abraham, in press) and may be important over sills in Puget Sound.

There is a vast literature on modeling boundary layer vertical turbulent exchange in stably stratified flows, and modelers have a large variety of algorithms from which to choose. Rodi (1980) has prepared a useful review of one class of models -- the numerical turbulence closures. While in principle, this type of mixing is the most clearly understood of any discussed here, many of the more complex calculation schemes are extremely demanding in terms of computation time and are limited to specific geometries. Most models are capable of calculating the surface and bed stress correctly, but most fail in regions where internal mixing processes are important. There is not at this time a consensus in the oceanographic community that any one of these more complex numerical schemes give better results for real bodies of water than much simpler eddy diffusivity schemes.

Internal mixing processes

Internal mixing processes are those that occur in the interior of flow, away from the boundaries. While internal

mixing is accompanied by localized turbulence, the ultimate cause is usually internal wave motion of one sort or another. Thus, internal mixing is normally concentrated in areas of strong stratification. That internal mixing depends on stratification for its existence may seem to contradict an earlier generalization that vertical exchange is inhibited by stratification. Internal mixing is, however, generally much weaker than boundary layer turbulence, so that stratification does indeed greatly weaken vertical mixing.

Several internal exchange mechanisms are probably active in Puget Sound, but little is known about their temporal and spatial distribution. When there is an internal tide in a two-layered flow, strong shears develop across the interface. This leads to the formation of high-frequency internal waves (called shear or Kelvin-Helmholtz instabilities) on the interface. After these grow sufficiently, they break and degenerate into turbulent billows. This is the characteristic mixing mechanism in salt wedges (e.g. the Fraser River Estuary; Geyer and Smith, 1987), occurs around the change of the tide in partially-mixed estuaries (Abraham, in press) and is almost certainly important in the pycnocline in Puget Sound in areas with substantial tidal currents.

It is common away from the boundaries of stratified estuaries for the stratification to be sufficiently large and the shear weak enough that neither boundary layer turbulence nor shear instabilities are possible. The random interaction of internal waves may still result in localized inversions in the density profile and, therefore, in a turbulent mixing. This process is believed to be of dominant importance in the interior of the ocean, is important in most partially mixed shallow estuaries and is probably the most important process in the interior of the deeper basins in Puget Sound. Whether this internal wave mixing is of overall importance in establishing the distribution of salt and pollutants in Puget Sound is open to question, because it is probably not important over sills during periods of active mixing. It has been parameterized by Gargett and Holloway (1984), but modification of their analysis is needed in estuarine environments that are typically more energetic than the ocean interior (Jay, 1987).

The above two internal mixing processes result in a two-way transfer of mass -- neither layer gains or loses mass. A net transfer of mass does occur when a turbulent fluid flows over an inviscid one and entrains fluid from below. The classical mass balance model of fjord flow assumes that the turbulent outflow in a thin surface layer is diluted by entrainment of fluid from the thick, nearly motionless lower layer. The relevance of this process to Puget Sound

is uncertain. Entrainment was neglected relative to exchange in mixing zones by Cokelet, Stewart and Ebbesmeyer (1984), but may not be negligible in all parts of the system.

The above external and internal processes are all primarily local; that is, the mixing at any location can be represented at least approximately in terms the tidal flow variables in that location. (In fact, lateral diffusion of boundary layer turbulence generated at topographic obstacles may exert a modifying influence on the mixing in some situations [Abraham, in press; Nelson, 1988], but this relatively small effect is neglected in most turbulence models.) There is at least one circumstance, however, in which non-local mixing cannot be neglected. This occurs when large-amplitude internal waves radiate away from a sill at the change of the tide, as has been studied extensively in Knight Inlet (Farmer and Smith, 1980). The breakdown of these interfacial waves is accompanied by considerable turbulent mixing, which in turn, plays an important role in the mass balance in this system. Because of the seasonal and tidal monthly variability in stratification and tidal forcing at Admiralty Inlet, it is likely that this process plays at some times an important role in the salt balance in Puget Sound.

Implications for Scientists and Managers

The above catalog of uncertainties is intended, not to induce despair, but to convince the reader that correct representation of vertical mixing processes should be a concern to all managers and scientists involved in modeling Puget Sound. There are, furthermore, several appropriate responses to this lack of knowledge. One is to focus research on vital weak points. Others relate to modeling strategy.

Observations

The two mixing mechanisms about which information for Puget Sound is most needed are shear instabilities and internal wave radiation from sills. Some of the uncertainty with regard to the importance of these processes to mixing in Puget Sound could be alleviated with relatively inexpensive field work that would rely heavily on acoustic echo sounding to obtain qualitative information. There is no need to mount in Puget Sound the much more extensive field program required to analyze these processes in detail -- there are other environments better suited to such studies. Work in the Fraser River Estuary has been used to construct an algorithm for shear instabilities in tidal flows (Geyer, 1985), and considerable work has been done in Knight Inlet on the sill mixing problem.

Model strategy

A good numerical model will usually be able to calculate surface elevations and transports with acceptable accuracy, because these are controlled by the relatively well-understood external mixing processes. The vertical distributions of flow and salinity must, however, be known if pollutant transport is to be understood in detail. These profiles are very sensitive to the nature and distribution of internal vertical mixing in a stratified estuary. Internal vertical mixing is thus, the "Achilles heel" of estuary models. Simple analytical calculations suggest, for example, that the strength of the two-layer gravitational circulation and the stratification in an estuary vary with, respectively, the inverse and inverse square of the vertical mixing coefficient K_m. Lack of knowledge concerning the dominant mixing mechanism at a given location can render K_m uncertain by a factor of 100, with disastrous results on our knowledge of the flow profile and stratification. Thus, there is a definite need for realism in design of modeling programs. Specifically, a balance needs to be maintained between the level of detail provided in a model and the accuracy of the mixing formulation. The present state of knowledge concerning mixing processes in Puget Sound provides little justification for applying highly detailed and sophisticated models to Puget Sound to obtain precise answers concerning current structure and pollutant transport. Much simpler box models, which do not require detailed knowledge of mixing processes, may at present be more accurate, even though they provide much less information.

This conclusion by no means justifies the neglect of the more sophisticated models. It is clear that the detailed information concerning the fate of pollutants that we would like to have will only be available from three-dimensional models. What is urgently needed in these models is simpler and more flexible turbulent mixing algorithms. For example, an eddy diffusivity with a stratification correction could be used near the sea bed and free surface, and a sheer instability or internal wave radiation closure in the interfacial region. For the moment, this desire to incorporate multiple mixing mechanisms would limit the resolution of the spatial grid that might be used. It may still be better, however, to employ several relatively simple mixing models that represent all the dominant mixing processes and accept the limitations on spatial resolution that this implies, rather than to use a more computationally intensive, higher-order turbulence closure on a dense spatial grid that cannot represent internal mixing processes correctly.

Finally, there is a practical need to evaluate numerical model representation of internal mixing phenomena in simple geometries (Abraham, in press). Because shear instabilities are the dominant mixing process in the salt wedge estuaries throughout the tidal cycle and in weakly stratified estuaries at the times of slack water, this mixing mechanism is relatively well understood and provides a good minimum test of model performance. Lawrence (1985) and Geyer (1985) have provided appropriate laboratory and field data sets for such tests.

In summary, lack of knowledge of internal vertical mixing processes presently limits the accuracy with which predictions concerning salt and pollutant transport can be made for Puget Sound. Field research is, therefore, urgently needed to determine the distribution and strength of major internal mixing mechanisms. Numerical modeling studies should be designed to make use of the available knowledge in the most effective possible way.

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Summary Statement

Alyn C. Duxbury*

Six papers were presented in this session on Circulation in Puget Sound. Two of the papers, by Lavelle and Chu, spoke to the numerical modeling of the Sound. However, these two studies are very different. Lavelle's modeling work looks at the Sound along a profile through the central basin from Admiralty Inlet in the north, to the Tacoma Narrows in the South. This model is used to study changing water characteristics over the vertical and to determine north-south horizontal velocity structure over the basin dimensions. This model shows how the entering seawater surges inward at depth. Excursion of isohalines in time can be used to show the progression rate of newly entered seawater along the length of basin. Cross channel variations are neglected. The velocity structure indicates the enhanced net circulation in the main basin and the requirement for recycling at the sills. Chu's model is a vertically layered model that predicts the tide and the horizontal tidal current patterns as averaged over the layers. The cell size of this model is 762 m x 762 m so fine scale motions are masked. The model predicts tide heights and phasing for the main basin as well as tidal currents required by changing water levels. Tidal currents and diffusion are then used to predict the transport of conservative materials released from a point source. Net transports resulting from velocity integration over tide cycles seem to be a little spurious. This may be due to the fact that model tidal current elipses do not always agree well with observed current elipses. Further research with this model should result in better approximations of transports.

Cannon and Mofjeld discussed what has been learned from observational data. Cannon described the direct measurement of currents over depth using current meters distributed over the vertical and cross channel. Integration of this data over tide cycles and cross channel areas has yielded estimates of net transports of water in the main basin due to estuarine circulation. Initial estimates of net fluxes are now believed to be too large; the error due to assuming that mid-channel flows are descriptive of the entire cross section of the main basin. A further problem lies with the ability to measure surface currents over long time periods. Reduction of the net transport to about one-half its original value means that recycling of water at the entrance to the main basin may be only 25%, rather than 50% as previously thought.

Mofjeld pointed out that the net circulation is not constant in time but has surges which occur related to periods of reduced tidal currents and sill mixing. These are often associated with the equinoxes. Strong density stratification at the mixing sill can also help suppress mixing and enhance stronger surges. The strong recirculation about Vashon-Maury Islands due to geographic orientation of channels plays a big role in enhanced circulation in the main basin but does not force the circulation in and out of the main basin at its entrance. The strong empirical fit between tidal current and mixing reduction and surging in the net circulation points out that sill mixing processes must be understood physically and incorporated into models to allow models of net circulation to work properly.

Cokelet presented an analysis of annual mean circulation derived from conservative water and salt budget techniques. This approach shows relative fluxes of water present in two layered estuarine flow and the recycling of water that occurs at mixing sills. These annual mean fluxes are then converted to transit times for water in subsections of the Sound. The water flux rates also allow the calculation of pathways and concentrations for conservative materials discharged into various subsections of the Sound. This technique is an excellent one for making a first cut at determining what areas of the Sound are more sensitive due to the long residence times of water and where discharges should be avoided if possible.

Jay presented a talk on the dynamics of fluid flow over the sills and in the main basin. He showed that the current shear at the sills coupled with a stratified water column can produce internal waves that break and dissipate resulting in mixing. This is the process that determines, to a large part, how entering seawater is modified at the sill and recycling. This relates directly to production of strong or weak surges of mid-depth or in the bottom water discussed by Lavelle, Mofjeld, and Cannon. In the interior of the main basin vertical mixing is controlled by other processes that are less dynamic. Direct studies of the mechanics of sill mixing processes are needed so they can be incorporated into models.

As Session Chair, I was very pleased by the presentations made by the six speakers and the effort that each speaker put forth to communicate his material to the diversified audience.

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TOXIC CHEMICALS

WHERE DO THEY COME FROM AND WHERE ARE THEY GOING?

Eric A. Crecelius,
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Roy Carpenter,
University of Washington
Session Co-Chairs

Introductory Statement

E.A. Crecelius[1] and R. Carpenter[2]*

The intent of this session on "Toxic Chemicals: Sources and Fates" is to expose those people concerned with the environmental quality of Puget Sound to current knowledge on this subject. An understanding of the sources and fates of toxic chemicals is necessary to make practical decisions aimed at reducing the level of toxic chemicals in Puget Sound.

During the last 15 years, developments in several disciplines have provided the tools and data necessary to examine sources and fates of toxic chemicals. These developments include: 1) analytical chemistry, 2) field sampling techniques, 3) sedimentation processes, 4) circulation modeling of Puget Sound, and 5) waste water management.

The first presentation deals with a very important subject, standard protocols for environmental measurements. Without high quality chemical results, it is impossible to evaluate distribution of chemicals in Puget Sound. The next two presentations deal with organotin compounds. These compounds, which are used in antifouling paint and biocides, are extremely toxic to some marine organisms. There is great interest in the concentration of these compounds in Puget Sound, but very little data are now available on the distribution. The five presentations scheduled for the afternoon session discuss sources and fates of heavy metals, hydrocarbons, and processes that influence the removal of these chemicals from seawater.

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IMPROVING QUALITY AND CONSISTENCY IN PUGET SOUND ENVIRONMENTAL MEASUREMENTS

John W. Armstrong[1] and D. Scott Becker[2]

Introduction

To maximize the utility of environmental information collected in any body of water, it is essential that data collected by different organizations and investigators be comparable whenever possible. Data that meet this criterion can be combined to assist in the development of comprehensive plans for evaluating, restoring, and managing the environmental quality of the water body. In many cases, however, data comparability among studies conducted by different organizations is limited because different methods were used to generate the data. The environmental manager is therefore faced with a patchwork of information that may be of minimal value for making system-wide decisions. One means of minimizing this kind of problem is to develop, and encourage the use of, standardized protocols for measuring environmental variables.

This paper describes a recent effort to develop standardized protocols for measuring selected environmental variables in Puget Sound, Washington. This effort is one component of the Puget Sound Estuary Program (PSEP), a multifaceted, multiagency program designed to protect and manage the environmental quality of the Sound. The protocols were developed to encourage all organizations that collect data in Puget Sound to use procedures that will generate high quality data that are comparable among different studies.

In describing the protocols standardization effort, we first outline our overall approach. Next, we discuss the major results of applying the approach to selected environmental variables that are measured in the Puget Sound area, and discuss the implications these results have for future efforts to standardize protocols in the Sound and elsewhere.

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Approach

Selection of Variables

To select the environmental variables having the highest priority for protocols development, a list was made of all the variables commonly measured in monitoring programs, intensive studies, and other kinds of investigations in Puget Sound. A representative group of local experts was then convened to evaluate each variable with respect to the following three criteria:

- The variable is measured by more than one organization. If a single organization measures a variable, it is likely that protocols are relatively standardized within the organization.

- Different protocols are used by different organizations to measure the variable. If different organizations use the same protocol, it is unlikely that data comparability is a major problem.

- The differences among protocols are substantial with respect to data comparability. If these differences are only minor, their resolution is desirable but lower in priority than resolution of major differences.

Following evaluation of all variables, a list was developed of those variables having the highest priority for protocol development.

Development of protocols

Each high priority variable was subjected to the protocol-development process outlined in Figure 1. The details of each step in this process are described below.

Development of draft protocol - For each variable, a draft protocol was developed prior to the workshop. The draft protocol gave workshop participants a common reference point and served to focus the workshop agenda. The draft protocol was mailed to workshop participants several weeks before the workshop to provide adequate time for review, and for discussions with colleagues that were not attending the workshop.

Workshop initiation - A workshop comprised of invited participants was convened to evaluate each draft protocol. Workshop participants were selected to represent most organizations that collect or use data for each environmental variable. Workshop participants were also selected to represent a range of viewpoints, from those of research scientists to those of managers.

At each workshop, the draft protocol was reviewed point by point. Each controversial item was discussed by the group, and a resolution was attempted. In some cases, a consensus could not be reached, and the item was left unresolved. In evaluating each protocol, emphasis was placed on generation of high quality data that would be comparable among different studies.

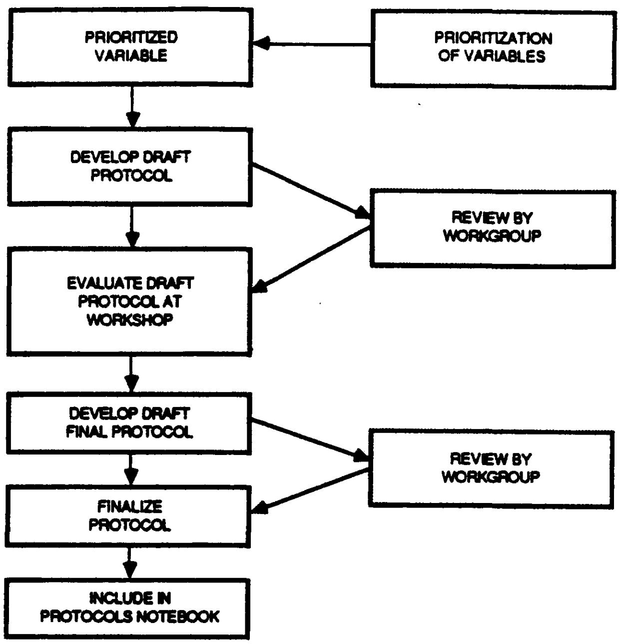

Figure 1. Overview of the protocol-development process.

Development of draft final protocol - Following each workshop, the draft protocol was revised to reflect the proceedings of the workshop. Specifications left unresolved at the workshop were acknowledged as such in the protocol. For most unresolved specifications the advantages and disadvantages of the various options were listed so that the user could decide which option was appropriate for a particular need.

The draft final protocol was sent to all workshop participants and other interested parties (local and throughout the U.S. and Canada) for final review. The purpose of this second review was to ensure that workshop participants agreed that the proceeding of the workshop were reflected accurately in the protocol, and to seek comments from interested parties who did not attend the workshop.

Finalization of protocol - After final review comments were received, individuals were contacted to resolve any major issues that they identified. Minor changes to the protocol were made without further discussions. After all outstanding issues were resolved, each protocol was finalized. A list of all contributors to the development of each protocol was included within the introductory section of each protocol.

Inclusion in Protocols Notebook - All final protocols were included in a specially designed, loose-leaf Protocols Manual. The loose-leaf format was selected to allow revisions and updates to be added to each protocol in the future, and to facilitate copying of individual protocols by interested parties.

Results

At present, protocols have been developed for the following eight topics:

- Station positioning
- Conventional sediment variables
- Organic compounds in sediment and tissue
- Metals in sediment, tissue, and water
- Benthic macroinvertebrate assemblages
- Laboratory sediment bioassays
- Microbiological indicators
- Fish pathology

These protocols have been distributed in a loose-leaf notebook to over 250 individuals, libraries, agencies, and private firms throughout the U.S. and Canada.

In developing the above protocols, considerable experience was gained in conducting the process in an effective manner. Some techniques worked and some did not. In this section, we describe the major principles we learned with respect to protocols development. We believe these principles can be used to assist others in developing standardized protocols elsewhere.

At the outset of this project, several criticisms or limitations were expressed concerning our goal of striving for consistency whenever possible in the collection and analysis of environmental samples from Puget Sound. Because these criticisms raise important points, the major ones are described below.

- The necessity of an effort to "standardize" sample collection and analysis was questioned. We found numerous instances where personnel from difference agencies used widely different protocols when sampling and analyzing the same parameter. In some cases, personnel within the same agency used different protocols.

- It was suggested that "standardizing" protocols would be stifling to research which might develop better methods. We did not propose that these protocols be dictated to anyone, but did propose that they be used for routine monitoring surveys and whenever an investigator has no preference in the protocols to be used in a program.

- Concern was expressed that the development of these protocols would encourage inexperienced individuals to collect and analyze samples. Inexperienced individuals have and will continue to collect and analyze environmental samples in the Puget Sound area and elsewhere. The development of these protocols should, at a minimum, improve the quality of the information being gathered by inexperienced and experienced personnel alike.

- It was suggested that the proposed protocols may not always reflect the "state of the art" in sampling and analysis. Although use of "state of the art" methods was a primary goal when developing each protocol, several other factors also required consideration. These factors included: the existing regional database, the cost and availability of various types of equipment, and the number of local laboratories that could perform certain analyses.

- Doubt was expressed that everyone in a region would use the same protocols. Some federal agencies may be required to use specific protocols which are different from the regionally developed protocols. In these cases, it will often be possible to compare these protocols and develop correction or conversion factors between the results of the analyses. In most cases, however, the desire of investigators to compare their data to information from other studies will encourage investigators to use these regionally developed protocols whenever possible.

In developing the protocols, we sought to reach a "consensus" among the regional experts and specialists in each of a number of fields. While reaching a consensus, or general agreement, on how a sample should be collected or analyzed may sound easy to achieve, it often was not. Many researchers, scientists, and technicians had collected information for a number of years in a certain way and were not easily convinced that a change in their approach was warranted. We found that the probability of reaching a consensus at a workshop was highest if we had a good facilitator, a detailed draft of the proposed protocol, the appropriate regional experts in attendance, and ample time to work through the details of the proposed protocols.

An experienced moderator or facilitator, who is knowledgeable in the specific topics being discussed at the workshop, is essential in the consensus-building approach. A skilled facilitator keeps the workshops focused and can bring out contributions from participants who may be reluctant to participate in group discussions or debates. In addition, the facilitator can draw out as many issues as possible for discussion before the entire group, thus reducing the number of written comments which may be received after the workshop. These "after the fact" comments are often difficult to address, because the workshop participants are no longer assembled to critique and debate the suggested protocol modifications. Finally, cooperation among workshop participants is enhanced if the facilitator is seen as having nothing to defend or gain as the final protocols are developed.

The consensus-building process also is enhanced when a detailed draft protocol has been completed and mailed to participants before each workshop. Workshop participants may then review this draft, discuss it with their associates, and bring their questions and comments to the workshop.

The selection of the invitees to the workshop, and their interaction with the facilitator, is very important since we found that many more comments are made verbally regarding the protocols than are submitted formally in writing. Invitees to each workshop were selected from universities and community colleges, state and federal resource agencies, county and city health departments, environmental consulting firms, and commercial laboratories. Every attempt was made to identify and invite those individuals that actually collected and/or analyzed environmental samples. These individuals were considered the ones who would have the most to contribute to, and learn from, the protocol development.

Workshops should not be extremely long, as interest and cooperative spirit may decline as workshop participants tire. All of our workshops were scheduled for 4-6 hours, and this seemed like an adequate amount of time to discuss most aspects of each protocol.

The establishment of protocols for marine sampling and analysis has been well received in the Puget Sound region. The process has been successful in bringing together investigators and technicians from universities, resource agencies, and the private sector to discuss common problems and find solutions. Numerous "requests for proposals" are now issued, and field sampling efforts planned, with the stipulation that the investigators either use the Puget Sound protocols or explain why other protocols would be more appropriate. The availability of these protocols also allows project managers who are unfamiliar with certain types of studies to specify detailed acceptable sampling and analysis requirements to potential contractors. Finally, these protocols will be an integral part of the Sound-wide monitoring program which is presently scheduled for initiation in 1988.

Conclusions

Final protocols have been established for eight topics. As part of PSEP, EPA, Region 10, is considering funding the development of several additional protocols in 1988: effluent bioassays, freshwater and marine water column sampling, and trawling for fish and crabs. These protocols would be particularly useful in permitted industrial discharge and Sound-wide monitoring programs. The Protocols Manual has been distributed to over 250 individuals, resource agencies, consulting firms, analytical laboratories, and universities throughout the U.S. and Canada. The protocols will undoubtedly increase the quality and comparability of information collected from Puget Sound. We hope that others can use our approach, as they seek to initiate similar efforts to improve data quality and utility in their regions.

FATE AND EFFECTS OF TRIBUTYLTIN IN THE MARINE ENVIRONMENT: AN UPDATE ON KNOWLEDGE

by

Rick D. Cardwell[1/]

Introduction

The purpose of this paper is to present an overview concerning the fate and effects of tributyltin (TBT) in the marine environment, emphasizing its sources and anticipated fate in marine waters.

In approximately the past four years, there has been vastly escalating concern about the aquatic environmental hazard posed by TBT, which is used for a variety of biocidal applications, most prominently as one of the two biocides (the other being copper) typically employed in antifouling paints. The reason for the interest in tributyltin stems from findings (EPA 1987a) that concentrations in marine waters could reach levels known to be chronically and sometimes acutely toxic to marine life. Some scientists also have suggested that the compound is persistent and possibly subject to biomagnification. On the basis of these assertions the public became alarmed that somehow a dangerous chemical had slipped through the regulatory net. In consequence, both Congress and many state legislatures moved to restrict use of TBT in antifouling paints. The legislation frequently superceded existing pesticide regulations because TBT has been regulated since 1972 under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA).

There has and continues to be a great amount of aquatic environmental research on TBT because of the need to define concentrations being encountered in situ by aquatic life, where TBT is transported and modified once released, and whether or not it is affecting aquatic life. This paper discusses these issues in five sections, specifically TBT's anticipated sources in Puget Sound, degradation pathways and sinks, bioaccumulation potential, and environmental concentrations versus aquatic toxicity. The latter is addressed in terms of water and sediment exposures. In the last section recommendations are made concerning management and research.

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Anticipated Sources of TBT in Puget Sound

Vessel hulls painted with TBT-containing antifoulant paints represent this biocide's most important source in Puget Sound, although areas where boats and ships are painted areas also are sources if waste disposal practices are improper. TBT also is used as a disinfectant, wood preservative, mildewicide in house paints, and biocide in cooling towers and pulp mills. It has also been used to control fouling in aquaculture nets, but this is an unregistered and hence illegal use in the United States.

TBT is typically one of two biocides used in antifouling paints; the other is copper. Many antifouling paints contain 5-7% TBT and 50-80% copper (EPA 1987a and Southern California Coastal Water Research Project 1973). Currently, there are three classes of TBT--1) contact leaching, 2) ablative, and 3) copolymer--and they differ in TBT release rates and durations of efficacy. TBT leach rates average 3.6 ug/sq. cm/day according to EPA (1987a), with the copolymer products giving the lowest overall leach rates (Anderson and Dalley 1986). TBT copolymer paints are expected to receive increasing use because of their ability to retain antifouling efficacy while maintaining acceptably low TBT release rates over several years. The oldest, contact leaching paints may be phased out because they offer only 1-2 years of antifouling control and probably will be unable to meet the governmental restrictions discussed below concerning TBT leach rates.

Concern about TBT probably stems from the fact that too many recreational boats have been using TBT-containing paints, some containing high-leaching formulations. These boats moor in areas (e.g., marinas) with limited ability to dilute the TBT leaching from the vessel hulls. The compound is used because of its high aquatic toxicity; thus controlling loading to the environment is the main issue.

Proposed EPA regulations (FR 52: 37510-37519, Oct. 7, 1987) intend to eliminate use of TBT on recreational vessels and to compel use of antifoulants that control leaching to low rates (i.e., <5 ug TBT leached/sq. cm/day), and improve pollutant control practices at shipyards. In general most TBT use will be restricted to ocean-going vessels (e.g., ships, tugs, barges). These restrictions, coupled with TBT's low to moderate persistence in receiving waters, should be more than sufficient to reduce environmental concentrations, in most instances, to levels below those causing both acute and chronic toxicity to aquatic life.

Fate of TBT In Marine Waters

Elevated TBT concentrations are expected in the surface microlayer, sediments and tissues of aquatic life that are being more-or-less continuously exposed to TBT. However, these should decline within weeks-months with decreasing exposure because TBT is degraded or removed from waters by microorganisms, aquatic plants and animals, mammals, photolysis, volatilization, and hydrolysis. TBT is degraded by progressive debutylation to dibutyltin, monobutyltin, and inorganic tin. The degradation intermediates are less hydrophobic and less toxic: for example, there is a 340-fold reduction in acute toxicity to the algae *Ankistrodesmus falcatus* between TBT and DBT and a 4-fold reduction between DBT and MBT (Wong et al. 1982).

Degradation Pathways and Sinks

TBT's octanol-water partition coefficient (Kow) is high enough (~ 2650, Table 1) to anticipate elevated concentrations in the hydrophobic, frequently lipid-enriched surface microlayer (Cleary and Stebbing 1987). A variety of contaminants with higher Kows (e.g., phthalates, polynuclear aromatic hydrocarbons) also should be concentrated in the microlayer, and the film may present a hazard to planktonic organisms, including fish eggs of certain species, and grazing intertidal invertebrates. However, whether an actual hazard exists needs to be investigated because TBT in the microlayer should be less bioavailable and may be more susceptible to degradation.

One of the most important pathways for reducing the concentration of readily bioavailable TBT in natural waters is via sorption to particulates. The sediment-water partition coefficient for TBT appears to be high enough (~3370, Table 1) to qualify sorption as the primary sink for TBT. In areas where there are continuous sources of TBT, most of the contaminant in the water column should be dissolved, but in the sediment, most will be bound. A portion of the particulate-bound TBT appears available to microorganisms, as Valkirs et al. (1986) have reported a half-life of 162 days in San Diego harbor sediments.

Table 1. Fate Properties of Tributyltin

Property	Most Representative Values	Typical Range
Octanol-water Partition coefficient (Kow)	2650	1450 - 4650
Sediment-water Partition coefficient (Koc)	3370	1670 - 6800
Bioconcentration Factor	3000	1500 -10000
Dietary Accumulation Factor	Remains to be defined	
Biodegradation Rates (T 1/2, days)		
• Algal	8.5 days	6 - 12 days
• Aerobic Microbial	8.5 days	6 - 12 days
• Anaerobic Microbial	>200 days	
Photolysis	21 days	1 - 90 days
Hydrolysis	Negligible	
Volatilization	Negligible	

Among pathways available for degrading TBT in natural waters, aerobic metabolism appears the most important. Most groups of plants and animals, from microorganisms through algae, fish and mammals (including man) appear capable of readily degrading TBT. The most important degradative pathway may be via algae; half-lives of 4-14 days have been reported, and they depend on such factors as the species and concentration of algae and water temperature (Seligman et al. 1987). Aerobic microbial and algal biodegradation appear comparable (Seligman et al. 1986), while anaerobic microbial metabolism may require more than 1 year (Envirosphere Company 1986)(Table 1).

Of the abiotic degradative pathways, photolysis is the only one of importance (Table 1). With ultraviolet radiation in the 300 nm range, photolytic half-lives are very rapid (~ 1 day), but can reach 89 days in direct sunlight (Envirosphere Company 1986). Photolysis should be most important for TBT contained in the surface microlayer and the surface of soils and intertidal sediments. Volatilization and hydrolysis appear to have negligible effects on degradation compared to the other processes.

Bioaccumulation and Biomagnification Potential

TBT is bioconcentrated (i.e., assimilated from aqueous solution) by fish and invertebrates at rates averaging around 3000-times the water concentration (Table 1). Rates are up to 10-times higher in bacteria and algae, but sorption rather than assimilation probably predominates. The degree of bioconcentration is much higher than that (<500) predicted using the octanol-water partition coefficient; binding of TBT in metallothionein pools is one possible explanation for the enhanced bioconcentration.

It has been commonly accepted that chemicals with Kow's less than 10000 and *in vivo* half-lives less than several weeks to months will not be biomagnified (Macek et al. 1979). Accordingly, biomagnification of TBT is unexpected, but to date there have been no valid, definitive investigations of biomagnification. There has been considerable controversy about this question. EPA (1987a) contends that the data of Evans and Laughlin (1984) and Laughlin et al. (1986) indicate that dietary accumulation is much more important than bioconcentration. However, neither of these studies were designed to produce valid estimates of dietary accumulation. Definitive tests are needed.

Environmental Concentrations Versus Aquatic Toxicity

Water exposures

Testing of EPA's acute and chronic toxicity has been sufficiently extensive to permit EPA (1987b) to publish provisional water quality criteria for aquatic life. TBT concentrations below 531 and 47 ng/l are expected to protect at least 95 percent of the marine species from acute and chronic toxicity, respectively. However, EPA set an advisory concentration of 10 ng/l because partial chronic tests of three species of clams and oysters indicated chronic toxicity down to 20 ng/l. However, these tests had drawbacks and more testing is necessary. In

addition Thain et al. (1987) and Gibbs and Bryan (1987) present data suggesting that shell growth in Pacific oyster and gonadal development in gastropods are affected between 2 and 20 ng/l.

Sufficient testing has been completed to define TBT's acute toxicity to aquatic life (Figure 1), but additional information is needed on its chronic toxicity, particularly to gastropods and bivalve molluscs, before definitive water quality criteria for chronic toxicity can be established. Chronic tests must, at a minimum, measure the standard chronic end points of survival, growth and reproductive success, in addition to investigating the developmental abnormalities reported by Gibbs, Thain, and their co-workers, among others.

In general TBT concentrations in the water column of natural waters appear to exceed EPA water quality criteria in areas where there is high recreational boat density and limited flushing (i.e., marinas). Elevated concentrations are expected, for example, in such areas as the Commencement Bay waterways, Des Moines marina, perhaps the lower Duwamish during low stream flow periods, and Shilshole Bay marina. Concentrations in comparable situations frequently are reported (see Marine Technology Society 1987) to exceed 100 ng/l, which would be chronically toxic to a number of species and acutely toxic to some. Concentrations, however, appear to decline very quickly proceeding away from the marina/harbor entrances, and estuaries in general are expected to possess TBT concentrations below the EPA advisory level of 10 ng/l. Elevated concentrations are not expected in the open waters of Puget Sound, Willapa Bay and Grays Harbor.

Sediment exposures

The bioavailability of TBT bound in the sediments is known to be greatly reduced, and hence one cannot equate measured sediment concentrations to toxicity data and EPA water quality criteria/advisory levels. Walsh (1986), working at EPA's Gulf Breeze laboratory, concluded that TBT's toxicity can be predicted by its octanol-water partition coefficient. Hence prediction should be possible using its sediment-water partition coefficient. Thus, for a sediment containing 50 percent dry solids, 5 percent organic carbon, and a Koc of 3000, less than 1 percent of the TBT in the sediments will be dissolved and hence readily bioavailable.

The simplest method for estimating safe concentrations of TBT in the sediments is to use the equilibrium partitioning approach and assume that most of the bioavailable TBT derives from the dissolved phase, even for detritivorous invertebrates. Assuming that TBT's sediment-water partition lies between 1670 and 6800, a sediment organic carbon content of 5%, and water quality criteria of 531 ng/l for acute toxicity and and 47 ng/l for chronic toxicity, sediments containing less than 44 and 181 µg/kg should not be acutely toxic, and those possessing less than 4 and 16 µg/kg should not be chronically toxic. The acute toxicity data of Salazar and Salazar (1984), and that of Walsh (1986), for example, suggest that higher concentrations may be necessary to elicit toxicity. Salazar and Salazar (1984) found that sediments containing 300-600+ ppb of TBT were not acutely toxic to the copepod *Acartia tonsa*, the mysid *Acanthomysis sculpta*, and a flatfish *Citharichthys stigmaeus*. Walsh (1986) determined that the range of acute toxicity of TBT-contaminated sediment to the grass shrimp (*Palaeomonetes pugio*) was between 1000 and 10000 µg/kg.

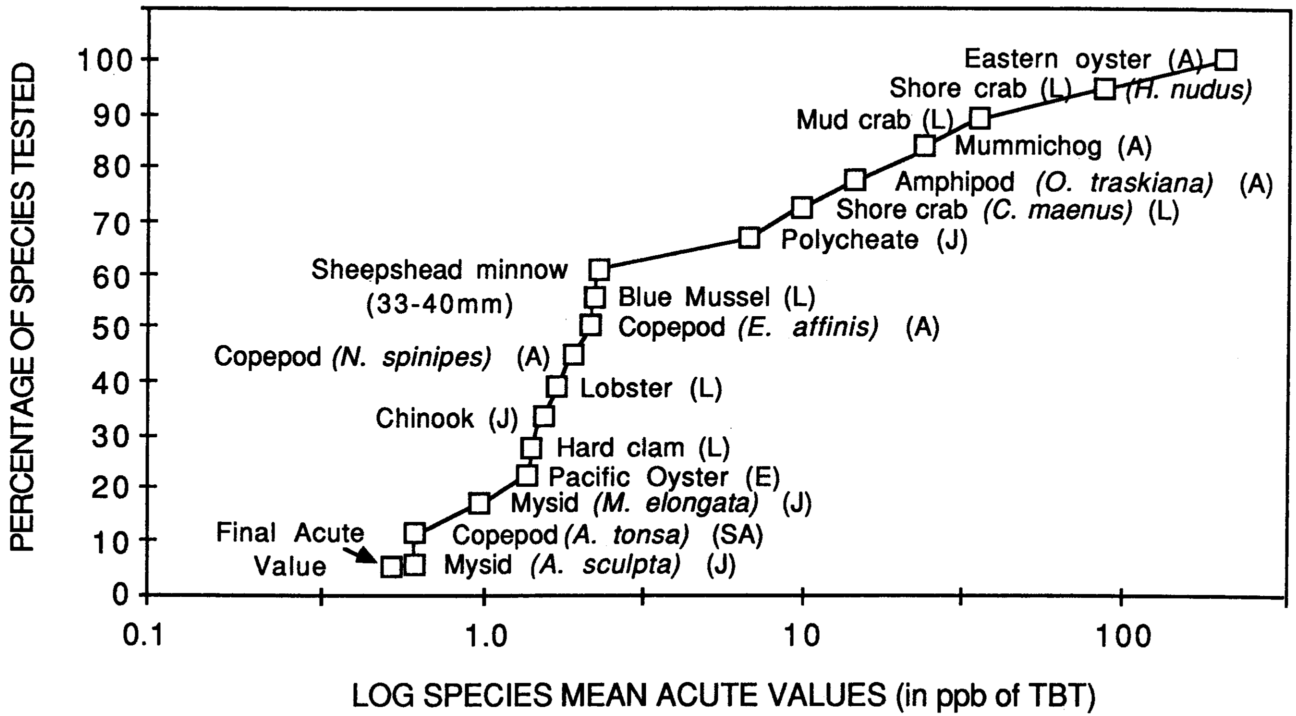

Figure 1. Relative sensitivity of marine organisms to tributyltin as percentage of species tested. Data from EPA (1987b). A=adult, J=juvenile, L=larvae, and E=embryo.

Recommendations for Management and Key Research Needs

Water quality management agencies should devote their attention to monitoring TBT in marine waters, assessing the implications of the wealth of research information that is expected to be published in the next several years, and periodically preparing aquatic ecological risk assessments of the monitoring data.

Pending EPA regulations are expected to greatly reduce the concentrations of TBT entering the marine environment. Monitoring of water, sediments and biota is necessary to track the efficacy of these regulations and identify any situations that need remediation. Monitoring should address the issue of bioavailability by distinguishing between dissolved and sorbed phases for samples collected from the water column and sediments. All methods should be able to distinguish the following compounds at concentrations well below those known to cause adverse effects: tetrabutyltin, tributyltin, dibutyltin, monobutytlin, and inorganic tin.

Although a great deal of scientific literature exists concerning the fate of TBT in aquatic environments and its effects on aquatic life and mammals, there are a few areas with important data gaps. These include TBT's bioavailability, its toxicity in the sediments, the importance of dietary accumulation and biomagnification, chronic toxicity to bivalve molluscs, and the magnitude of the difference between acute and chronic toxicity. Local and state agencies do not have the resources to perform this research. However, EPA is requiring TBT manufacturers to perform all of these studies, and summaries of these data will be available. Because of intense interest in TBT by the scientific community, there has and continues to be extensive publication of research findings. Management agencies will be able to use these data to evaluate and manage the risk of TBT in Puget Sound.

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Analysis of Tributyltin and Related Species in Sediments and Tissues

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Introduction

Concern about organotin use was initially highlighted by its impact on commercial shellfisheries, especially in France and the United Kingdom. There is however now, evidence of detrimental effects in other aquatic organisms (Hall and Pinkney, 1985). Legislation in several countries and states in the U.S.A. has been enacted in an effort to control and mitigate environmental damage. Butyltins (e.g. tributyltin(TBT)) enter the marine environment primarily through the use of antifouling paints. Other inputs can include municipal waste water or effluents from pulp and textile mills, breweries, and electrical generation plants where TBT is used as a slimicide (Snoeij, et al., 1987). TBT has been found to be extremely toxic to marine biota. Both the target organisms that TBT is intended to inhibit as well as non-target organisms are affected. Levels in water in the low ng/L range can cause detrimental effects in oysters (Hall and Pinkney, 1985; Thain et al., 1987).

Although methods for the analysis of organotins in water are fairly well established (e.g. Mathias et al., 1986), methodology for the measurement of organotins in sediment and tissue is more limited. A research need important to the policy and decision making processes involved with the management of butyltins in the environment, is the establishment of protocols for their measurement in water, sediment and tissues. While water levels of TBT can fluctuate dramatically over days and even hours, sediments serve as an integrator and long-term sink for a number of hydrophobic contaminants, including butyltins. Sorption coefficients for TBT on sediments are reported to range from 1000 to 10,000 (Unger et al., 1987; Randall and Weber, 1986). The sediment bound contaminants may be available for uptake by benthic organisms and may serve as a source of contaminants to

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the water column through diffusive flux and resuspension/desorption events. Thus the development of precise and reliable methods for the analysis of butyltins in marine sediments and tissues is urgently needed. Accordingly, our laboratory has devoted considerable effort toward development of protocols for determination of butyltin species (i.e.tetrabutyl-, tributyl, dibutyl-, and monobutyltin) in sediments and tissues.

Methods

A number of steps are required for the analysis of organotins. They include extraction, derivatization, clean-up and analysis. Each is important to the overall determination. We investigated a number of extraction methods, solvents and clean-up procedures prior to deciding on the following procedure (Figure 1.). Briefly, it involved extraction of sediment or tissue with methylene chloride and tropolone using sodium sulfate as a drying agent. The extracted organotins were converted to their hexyl derivatives through the Grignard reaction, and following a silica /alumina clean-up, the organotins were analyzed by GC/MS. Quality assurance measures were included as an essential part of our protocol. Surrogate spikes, calibration standards, blanks, spiked samples, reference materials and replicate analyses were used to evaluate performance. Using this method, high recoveries of the tripentyltin (TPT) surrogate spike were observed in the two reference sediments, SQI and Duw III, and spiked blanks (99%±20, 96%±8 and 89%±18 respectively). For 27 environmental samples, the overall recovery of TPT was 101%±22. The limits of detection for TBT in these sediments ranged from 1 ng/g to 3.6 ng/g dry wt.as Sn.

This well tested method was then applied to sediments and liver tissue (from English sole) collected in several areas of Puget Sound(Figure 2.). Sediments were collected from the Duwamish West Waterway (3 stations), from Elliot Bay along the Seattle Waterfront (3 stations, from Piers 65 to 69), from Everett Harbor (two stations)and from the reference area President Point (3 stations). Sediment was sampled using a modified Van Veen grab. Three grabs were made at each station and composited. Surface samples of the top 2 cm of sediment were collected in glass jars and stored on ice. Samples were frozen upon return to the laboratory and then analyzed within one month. English sole were also captured in the above locations using an otter trawl. The fish were weighed, measured and necropsied within one hour of capture and liver tissues frozen in liquid nitrogen.

Figure 1. Analytical Procedures for Butyltins

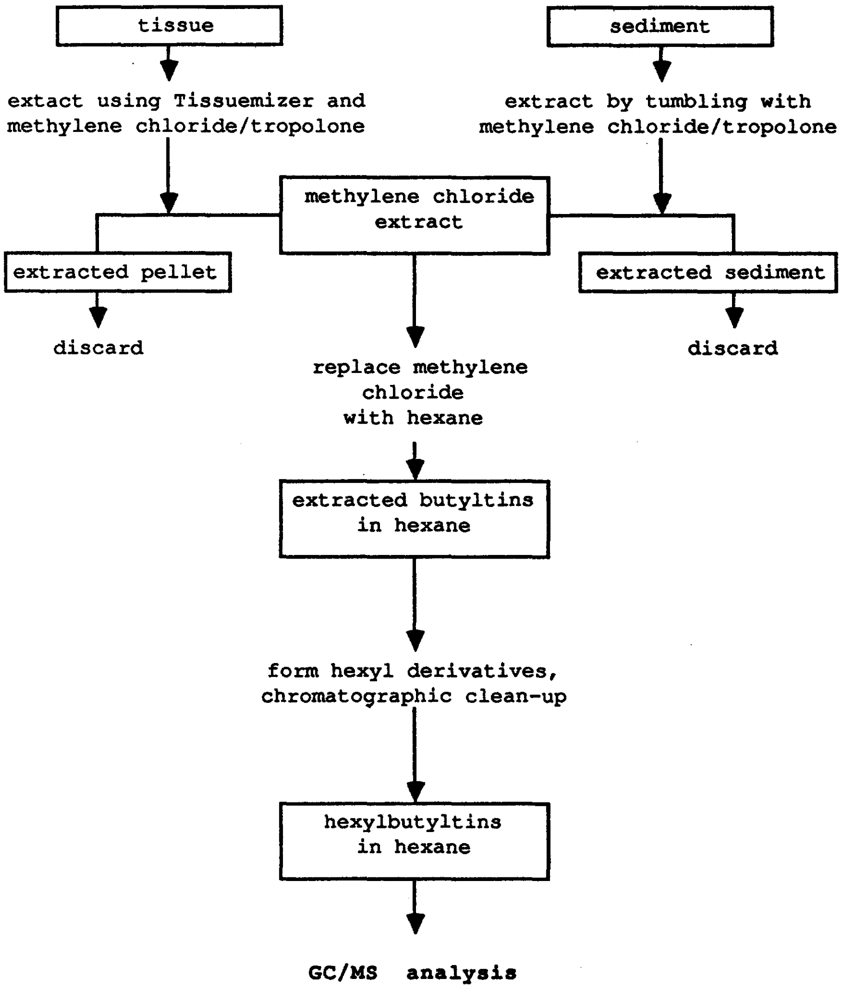
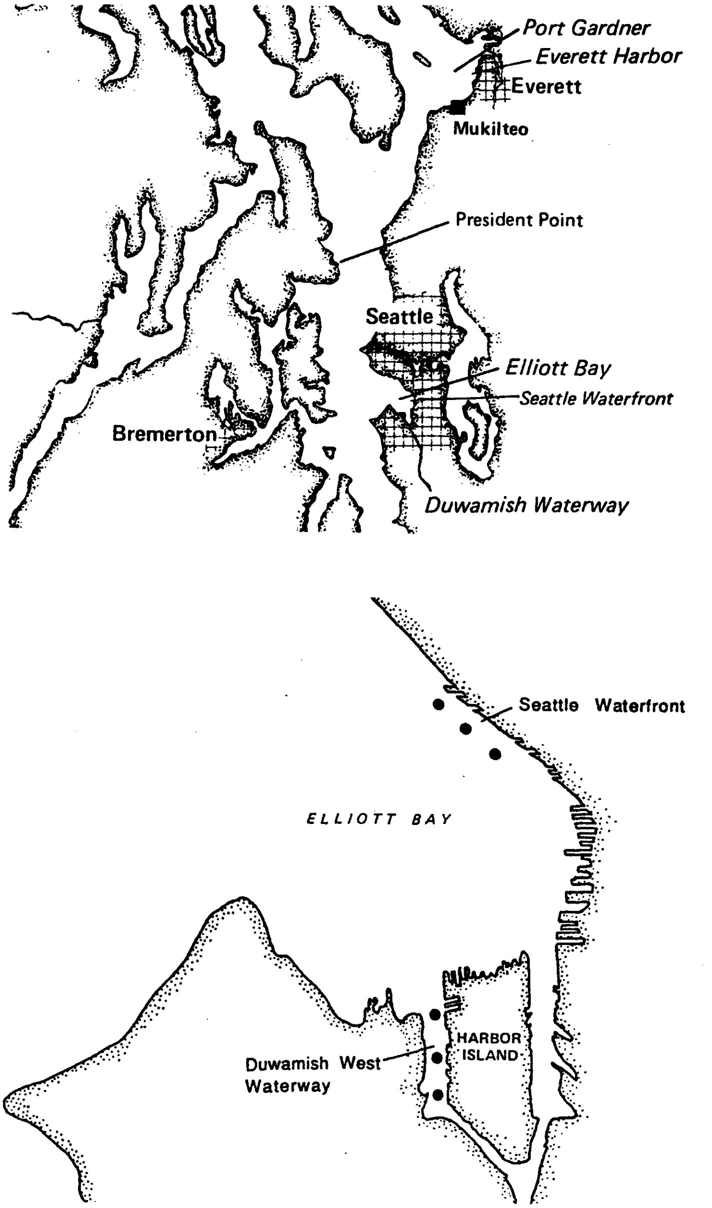


Figure 2. Locations of sampling sites in Puget Sound. Closed circles (●) on enlarged map (bottom) show stations in Duwamish West Waterway and along Seattle Waterfront where sediments were collected.



Results

High levels of butyltins were found in the Duwamish West Waterway. For example, at some stations in the Duwamish, the TBT concentrations were over 1 ng/g TBT dry weight expressed as Sn. Total butyltin concentrations ranged from 850 to 1920 ng/g. TBT was also measured in the sediments from the Seattle Waterfront stations (mean TBT concentration was 70 ng/g) and the Everett Harbor sample taken ~0.3 mi south of Pier 1 (TBT concentration of 16 ng/g). Butyltins were not found in the samples from the reference site, President Point (detection limits were all < 3.9 ng/g dry weight as Sn) nor in sediments from an area 2/3 mile north east of Pier 1 in Everett near Buoy #3.

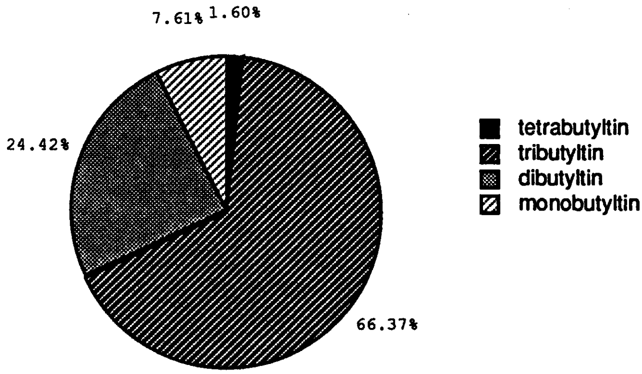
The presence of other butyltin species, particularly dibutyltin (DBT), was observed in the Duwamish and Seattle Waterfront samples, although the proportions of the four butyltin species differed in these sediments (Figure 3). The concentrations of dibutyl- and monobutyltin (MBT) in the Duwamish sediments were approximately 3 and 10 times less than the concentration of tributyltin, respectively. In the Seattle Waterfront sediments however, the concentration of dibutyltin was comparable to the TBT concentration (mean concentrations of 56 and 70 ng/g dry weight as Sn for DBT and TBT respectively). No tetrabutyltin was observed in the Seattle waterfront samples (detection limits were 1.0 to 9.6 ng/g dry weight as Sn).

Butyltins were present in liver tissue from English sole captured in both the Duwamish West Waterway and the Seattle Waterfront sites. Unlike the sediment samples, where TBT was found in higher concentrations than the other butyltins, DBT was the predominant species measured in the livers (>85% of the butyltin content was as DBT in the samples from the Duwamish Waterway). TBT levels ranged from non-detectable (detection limits <22±25 ng/g dry weight as Sn) in fish from the Seattle Waterfront to 220± 146 ng/g in the fish from the Duwamish. Neither tetrabutyltin nor monobutyltin were observed in the liver tissues from the above two sites. None of the four butyltins were detected in livers from President Point fish. The limits of detection in these tissues were 4.9, 24, 71 and 14 ng/g as Sn for tetra-, tri-, di-, and monobutyltin respectively.

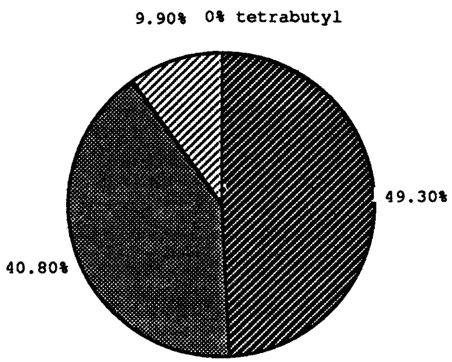
Discussion

Little is known about TBT contamination in Puget Sound. Water samples from Bremerton were reported to contain ~1.1 ng/L TBT (as Sn) in commercial and recreational vessel moorage and repair facilities (Grovhaug et al.,

Figure 3. Proportions of Butyltins in Sediments



DUWAMISH SEDIMENT



SEATTLE WATERFRONT SEDIMENT

1986) while TBT was not found in U. S. Naval Operational areas. Water levels in two marinas near Indian Island, Puget Sound were reported to be 27-52 ng/L TBT (Grovhaug et al., 1986). Our results show that TBT, DBT and MBT are present in certain Puget Sound sediments and have reached the part per million levels in some cases. The differing profiles of butyltin species in the various sediments could be due to a number of biological and/or geochemical factors including differences in rates and types of degradation reactions, in the butyltin profiles of inputs and in processes such as volatilization, resuspension, adsorption and desorption (Thain et al.,. 1987). More research will be needed to explain the reasons for, and importance of these differences.

There are a number of other gaps in our knowledge regarding the presence, fate and effects of TBT in the environment. Some of the areas in which information is most needed include determination of actual levels of TBT that are harmful to important aquatic species, the long term fate of TBT in the marine environment, the current levels of TBT in water, sediment and tissues (in Puget Sound and other estuaries), the bioavailability of sediment bound TBT and whether native aquatic populations have been impacted. However, prior to obtaining information in any of these areas, high quality analytical procedures are needed.

Hence, the methods we have developed can contribute to narrowing the information gap in several of the above areas and will be of great value in aiding management decisions regarding TBT contamination in Puget Sound. Management tools available for dealing with TBT include:(a) initiating monitoring programs and developing criteria for acceptable levels in water, sediment and tissues; (b) investigating boatyard practices to determine ways to improve application, removal and disposal procedures; (c) development of educational programs to advise boaters, boatyards, marina suppliers, etc., about TBT paints and acceptable methods of handling them.

In conclusion, we have developed and tested, comprehensive methods for the analysis of butyltins in sediments and tissues and have applied them to environmental samples. The data have clearly shown that butyltins are present in sediments from various areas of Puget Sound and that these compounds have found their way into resident aquatic life. The information from this initial survey points to the need for future expansion of these investigations in Puget Sound and other estuaries in the United States.

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Equilibrium Exchange of Metals During Freshwater/Seawater Mixing

Charles D. Boatman*

Introduction

As population in the Puget Sound basin increases, the demand for freshwater for municipal and industrial uses will increase along with the discharge of this water into the Sound as waste. Physiochemical processes which occur during the mixing of freshwater with seawater play an important role in controlling the concentration and distribution of pollutants in the estuarine environment. The partitioning of many elements between the solution phase and the suspended particles undergoes dramatic changes in response to changes in pH, ionic concentration and ionic composition. Certain processes such as flocculation, adsorption, precipitation, and co-precipitation will act to remove metals from solution during mixing. Other processes such as dissolution and desorption will act to release metals bound to suspended particles and counteract the removal processes.

The two most important counteractive processes which affect the partitioning of metals between solution and the suspended particles during mixing are desorption and flocculation (Li et al., 1984). One of the primary mechanisms for desorption during estuarine mixing is considered to be ion exchange (Olsen et al, 1982). This paper presents a model which describes the equilibrium partitioning of exchangeable metals on suspended sediments throughout the mixing of freshwater and seawater. As an example, data for Mn^{2+}, Cu^{2+}, and Cd^{2+} from the Duwamish River estuary (Paulson et al., 1984) will be used to illustrate the particle interactive behavior of these metals related to exchange desorption during estuarine mixing. Other possible applications will also be presented.

Model Description

The estaurine mixing model is a combination of a multi-element multi-ligand solution speciation model which includes organic complexes similar to the model of Mantoura et al. (1978), and a quasi-thermodynamic equilibrium ion exchange model (Boatman, 1985).

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The solution speciation model determines to what extent the metal ions in solution are complexed with solution ligands such as chloride, carbonate, or humics, and what fraction of the metal exists as a the free uncomplexed ion. The ion exchange model then determines the equilibrium partitioning of the free metal ion between the suspended particles and the solution. Clay minerals in the form of river-borne suspended sediments are used as the model particles.

The ion exchange model assumes that the trace metal cations (such as Mn^{2+} or Cu^{2+}) compete with the major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) for negatively charged exchange sites on the surfaces of suspended sediments. The total amount of metal adsorbed will depend on: 1) the chemically available concentration of the free metal ion in solution (known as the activity); 2) the activities of the major cations it is competing with, and 3) the relataive affinities of the major cations and the metal for the exchange sites. The amount of metal adsorbed and the concentration in solution can therefore be predicted for any mixing fraction of freshwater with saltwater.

Duwamish River Estuary

Study area

The Duwamish River estuary was chosen as an example application since it is probably the most studied estuary tributary to Puget Sound and has the necessary data available for input to the model. In particular, the recent metals data from the Duwamish collected by the PMEL group at NOAA (Paulson et al., 1984) were considered to be a good and reliable source of data for developing and testing the model. Data for the major dissolved ions and suspended sediment concentrations for the Duwamish were taken from Santos and Stoner (1972).

Model conditions

Two separate river flow conditions were modeled. Low flow conditions were assumed to be less than 20 m^3/sec and high flow conditions were assumed to be greater than 60 m^3/sec. Based on historical data, high flow conditions generally occur during the winter and spring months (December through May) and low flow conditions generally occur in the summer and early fall (July thruough October). Data from Santos and Stoner (1972) were used to estimate major ion and suspended sediment concentrations at the two flow conditions. Suspended sediment concentrations were assumed to be 20 mg/L under low flow conditions and from an average of 200 to a maximum of 1,000 mg/L under high flow conditions. Suspended sediment concentrations in the seawater were taken to be 1 mg/L in all cases (Curl et al, 1987).

Suspended sediments were assumed to remain at the river water concentration until about 10 o/oo salinity at which time there was an assumed linear decrease in concentration to the 1 mg/L seawater concentration. This is consistent with the data from Curl et al. (1987) and with the concept of a turbidity maximum zone which peaks

downstream of the initial mixing zone. A constant ion exchange capacity of 0.3 equivalents/kilogram of sediment was assumed throughout the modeling study (Brannon et al., 1980).

Modeling Results

Solution composition

Fig. 1 shows the model results for the major cations, anions, and pH under low flow conditions for the Duwamish River estuary. The most obvious and striking observation from these results is the dramatic increase in concentration of the major cations in the initial stages of mixing. This is also true for chloride and sulfate. These ions (except for calcium) increase by one to two orders of magnitude in concentration within the first 5 o/oo salinity.

These results imply that the major cations will be able to displace exchangeable metal at very low salinities. In addition, the large increase in chloride and sulfate concentrations (Fig. 1a) will result in a decrease in the free metal ion concentration available for adsorption for those metal ions which form strong solution complexes with these anions. This is the case for manganese and especially for cadmium which forms very strong complexes with chloride. This increase in solution complexation will act to enhance the desorption of metal ions.

Apparent exchange constant

The net result of the changes in solution composition on the partitioning of metals between the solution and suspended sediments during estuarine mixing is a decrease in the amount of metal adsorbed. Fig. 2 illustrates the decrease in the capacity of the suspended sediments to adsorb metals as a function of salinity in terms of an apparent exchange constant under high and low flow conditions. The exchange constant is simply the ratio of the equilibrium concentration of exchangeable metal on the suspended sediment expressed as moles/gram of sediment to the concentration in solution expressed as moles per milliliter of solution. This yields units of mL/g which are the units of the distribution coefficient (K_d) typically used in adsorption studies.

As expected, there is a large decrease in the exchange constants of from one to two orders of magnitude for manganese and cadmium in the initial mixing region of less than 5 o/oo. The constant decreases more rapidly for cadmium than manganese due to its being more strongly complexed in solution as the salinity increases. Copper is not strongly adsorbed either in freshwater or seawater and is about 1,000 times less strongly adsorbed than either manganese or cadmium in freshwater. This can be attributed to the fact that copper is very strongly complexed by dissolved organics (humic matter) in the riverwater and then by hydroxide and

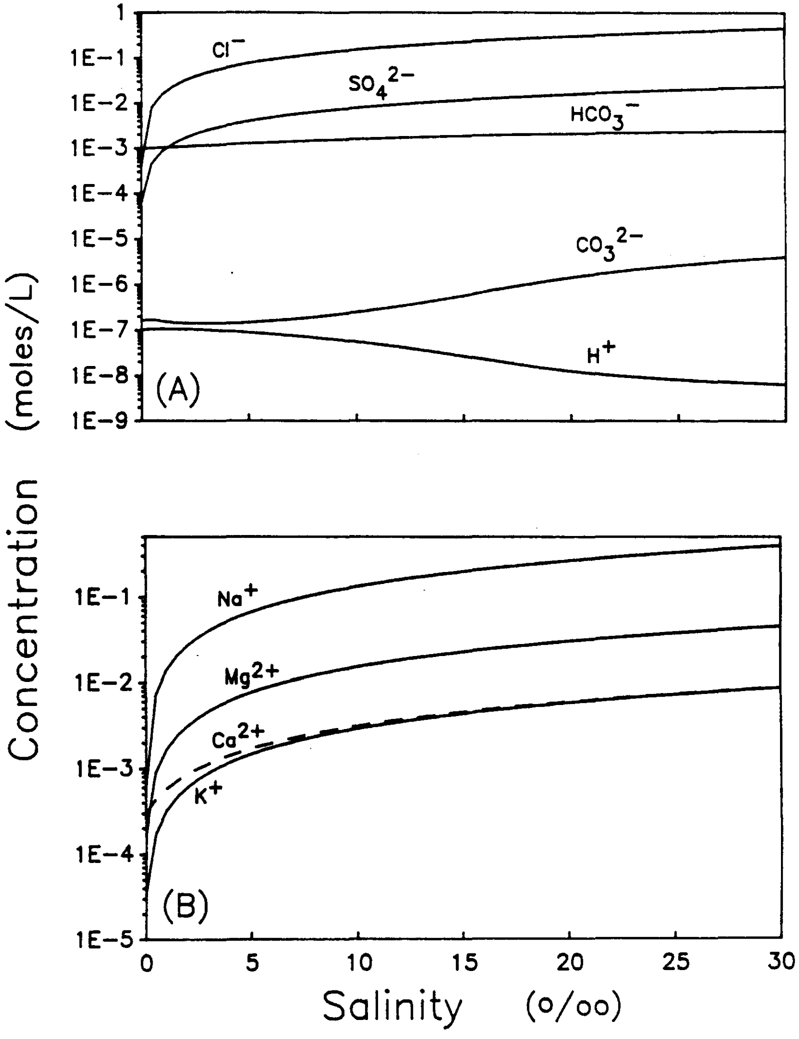

Fig. 1. Concentrations of (a) major anions and pH and (b) the major cations in the Duwamish River estuary under low flow conditions.

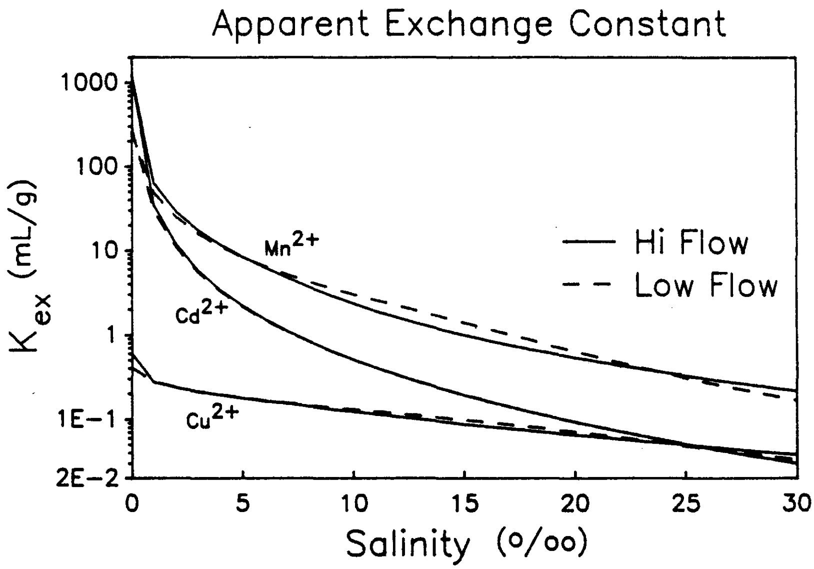

Fig. 2. Apparent exchange constant for manganese, cadmium, and copper in the Duwamish River estuary under high and low flow conditions.

carbonate in the saltwater so that there is very little free metal ion available.

The constants in riverwater at zero salinity are greater for the high flow case than the low flow case because the concentrations of the major cations and anions are lower during high flow conditions. This is seen to be more important for manganese and cadmium than for copper.

Metal concentrations during mixing

We can now finally put together the combined effects of changes in solution composition and the apparent exchange constant to predict the concentration of metal ions during estuarine mixing for the Duwamish River Estuary. Figure 3 shows the results of the predicted concentrations for manganese, cadmium, and copper at three suspended sediment concentrations. The free metal activity is shown along with the total solution concentration for comparison. The total solution concentration is what would be measured analytically from field samples, while the free ion activity is what is chemically active and available for adsorption and for uptake by estuarine organisms (Engel et al., 1981).

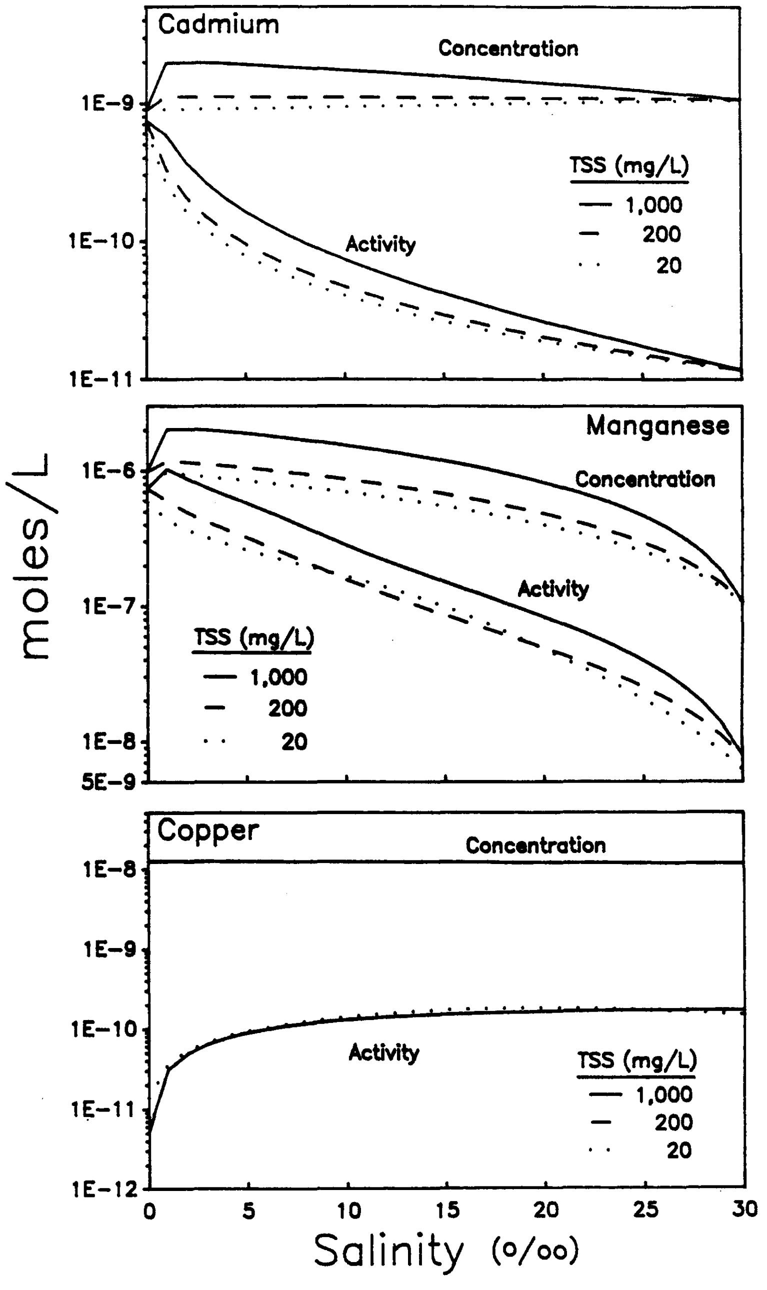

Fig. 3. Predicted total concentration and free metal ion activity for cadmium, manganese, and copper in the Duwamish River estuary. Total suspended solids (TSS) concentrations of 1,000 and 200 mg/L are for high flow conditions, 20 mg/L for low flow.

Under low flow conditions with 20 mg/L suspended sediment concentration, there is no significant increase in solution concentration predicted from the model. However under high flow conditions, there is a significant increase in solution concentration for manganese and cadmium. Copper concentration is relatively insensitive to flow conditions and suspended sediment concentrations due to its small apparent exchange constant (Fig. 2).

These results are qualitatively similar to those of Paulson et al. (1984) who found that both manganese and cadmium were measurably desorbed in the 1 to 4 o/oo salinity range in the Duwamish Estuary. Copper was not found to be desorbed in their study but it was found to be removed by flocculation of what were assumed to be Cu-organic colloids. This is also consistent with the model which would predict no desorption to occur due to the presence of soluble copper organic complexes.

Other researchers have found that cobalt, zinc, nickel, cesium, barium, and radium in addition to manganese and cadmium will be desorbed from river suspended matter during mixing (Van der Weijden et al., 1977; Hanor and Chan, 1977; Li and Chan, 1979; Li et al., 1984). Although these metals were not modeled for this report, it can be assumed that they would also exhibit similar behavior to manganese and cadmium.

<u>Summary</u>

1) The model qualitatively predicts desorption behavior in the Duwamish River estuary for manganese, cadmium and copper.

2) For manganese and cadmium, and possibly for a number of other metals, the amount of metal which will be desorbed will be dependent on the ionic concentration of the freshwater source and the concentration of suspended sediments.

3) For those metals which do desorb, fluxes of dissolved metals from freshwater sources with high sediment loads can be significantly enhanced by desorbtion.

4) Metals which form strong complexes with freshwater organics or other freshwater ligands (e.g. copper, mercury, iron, and aluminum) are most likely not to be associated with suspended sediments and will not exhibit desorption.

Based on these results, situations in which we might expect to see appreciable desorption would include:

- CSO events with low ionic strength effluent and high sediment load.

- Disposal of dredge sediments from a fresh or brackish water environment to a saltwater environment especially from a metal-rich contaminated dredge site.

- o Possibly from the disposal of dredge sediments from a metal-rich contaminated dredge site in a saltwater environment if concentrations of metals in the interstitial water were high.

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Copper and Lead in Puyallup Valley Streambed Sediments

By James C. Ebbert and Edmund A. Prych*

Abstract

Copper and lead concentrations in the clay-size fractions of bed sediments from many sampling locations in the lower Puyallup and White Rivers were larger than concentrations in uncontaminated sediments from the headwaters of these streams. Concentrations of copper, but not lead, in river bed sediments tended to be larger than in bottom sediments from Carr Inlet of Puget Sound, which are believed to be uncontaminated. Concentrations of copper were similar to concentrations in samples from areas of suspected contamination in Commencement Bay, but lead concentrations were lower. Concentrations in Puyallup River bed sediments were largest along the bank downstream from a municipal sewage treatment plant and a major storm-water outfall.

Concentrations of copper in small-stream bed sediments were similar to concentrations in sediments from the headwaters and from Commencement Bay, but were larger than in sediments from Carr Inlet. Lead concentrations in the clay-size fraction of bed sediments from small streams in the urbanized and industrialized areas of the lower Puyallup valley were larger than concentrations in sediments from the headwaters, from the lower Puyallup River, and from Carr Inlet, but were similar to concentrations in Commencement Bay sediments.

Introduction

In 1981, the U. S. Geological Survey, in cooperation with the Puyallup Indian Tribe, began a study of the ground- and surface-water resources of the lower Puyallup River valley and adjacent uplands in western Washington. The study included an investigation of ground- and surface-water quality, a statistical evaluation of the streamflow characteristics of small streams, and the construction of a numerical model to assess ground-water availability.

One facet of the surface-water quality investigation involved using concentrations of trace elements in streambed sediments to help evaluate stream quality. Because trace elements tend to sorb onto sediments in streams, and because sediments accumulate on streambeds over some period of time, bed sediments integrate the effects of upstream contaminant sources. The purpose of this paper is to characterize copper and lead concentrations in bed sediments of streams that discharge into Commencement Bay of Puget Sound, and to compare them with concentrations in some bottom sediments of Puget Sound.

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Methods and Scope

Sediment samples were collected in 1983 and 1984 from the Puyallup and White Rivers and from seven small streams that discharge, either directly or through other streams, into Commencement Bay (fig. 1). These streams include Swan, Clarks, Diru, Wapato and Hylebos Creeks, an unnamed tributary at Hylebos Creek, and Fife Ditch. Bed-sediment samples were collected at each site during one or two low-flow periods. Also, three samples that were believed to represent relatively uncontaminated sediments were collected. Two were bed sediments collected in the headwaters of the Puyallup and White Rivers, and the third was from a gravel pit near the city of Puyallup. These samples will be referred to as headwaters samples.

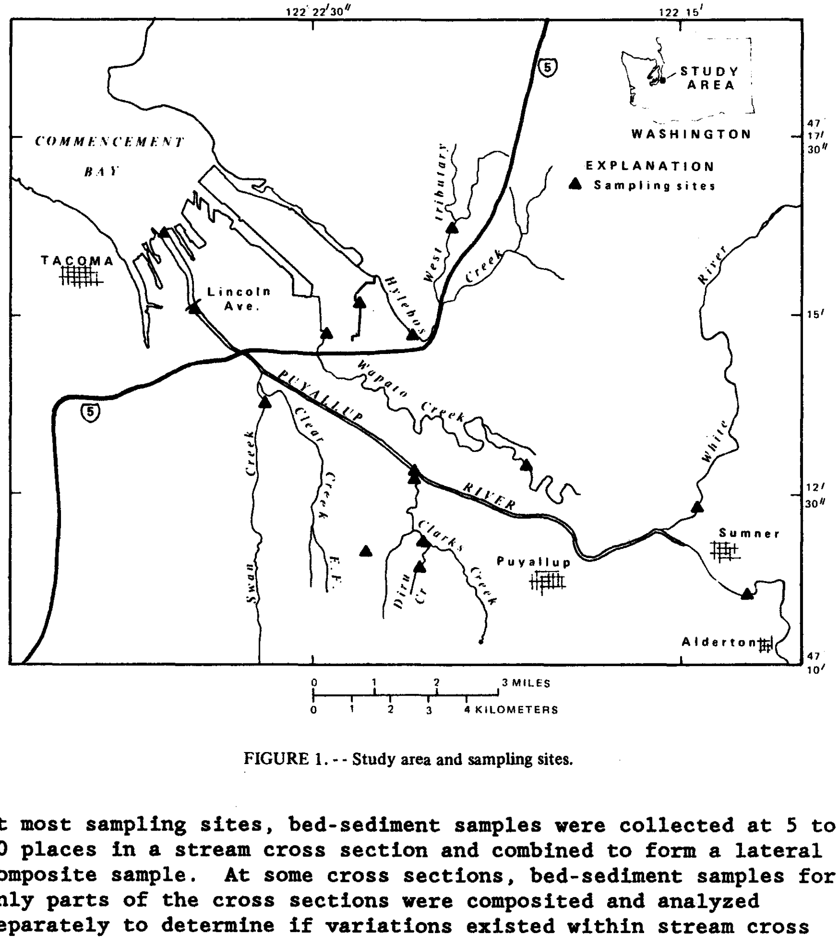

FIGURE 1. - - Study area and sampling sites.

At most sampling sites, bed-sediment samples were collected at 5 to 10 places in a stream cross section and combined to form a lateral composite sample. At some cross sections, bed-sediment samples for only parts of the cross sections were composited and analyzed separately to determine if variations existed within stream cross sections. Sediment samples were separated into sand-, silt-, and clay-size fractions prior to trace-element analyses. Samples were sieved in the field using native water to remove particles larger than 2 mm (millimeters). In the laboratory, the sand-size fraction (0.062 to 2 mm) was isolated by wet sieving with distilled water.

The silt-size fraction (0.002 to 0.062 mm) was separated from the clay-size fraction (less than 0.002 mm) by settling and centrifugation in distilled water as described by Jackson (1969).

The sand-, silt-, and clay-size fractions of sediment samples were analyzed separately to determine total concentrations of arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver, and zinc. Total trace-element concentrations represent the sum of the elements present within the crystal lattice of minerals as well as those held at the surface in exchange sites, on oxide coatings, or in organometallic complexes. The coefficient of variation for laboratory determinations of concentrations was 10 percent or less. The coefficient of variation caused by the combination of sampling, processing, and laboratory errors is estimated, on the basis of only two duplicates, to be about 20 percent.

For brevity, this paper presents only the results of the copper and lead determinations for bed sediments. The results of these and other determinations, which included inorganic and organic constituents in bed sediments, suspended sediments, and in water, are reported by Ebbert and others (1987).

Results and Discussion

Bed sediments

Concentrations of copper and lead in some of the bed-sediment samples collected in the lower Puyallup Valley were larger than concentrations in headwaters samples (fig. 2). The largest differences were in the silt- and clay-size fractions. This distribution of concentrations suggests that some sediments from the study area were enriched (contaminated) with copper and lead. The increase in concentrations with decrease in particle size indicates probable sorption of copper and lead onto the surfaces of sediment particles. Fine-grained sediments provide a larger surface area for substrates that enhance adsorption, and therefore copper and lead concentrations would likely be larger for fine-grained sediments than for coarse-grained sediments (Horowitz, 1984).

Concentrations of copper and lead in the clay-size fraction of a large percentage of samples from the Puyallup and White Rivers were larger than those in headwaters samples (fig. 2). Such was not the case for the silt- and sand-size fractions. Concentrations of lead in all three size fractions of a large percentage of samples from the small streams were larger than concentrations in headwaters samples (fig. 2). However, copper concentrations in all fractions of the small stream samples were similar to those in headwaters samples.

Because concentrations in the clay-size fraction are the most sensitive indicators of contamination, those data were selected for closer inspection and are shown in figures 3 and 4. Copper and lead concentrations in the clay-size fraction of bed sediments collected from the left (facing downstream) half of the Puyallup River at Lincoln Avenue during a base-flow period in August 1983 (fig. 3) were eight and three times larger, respectively, than concentrations

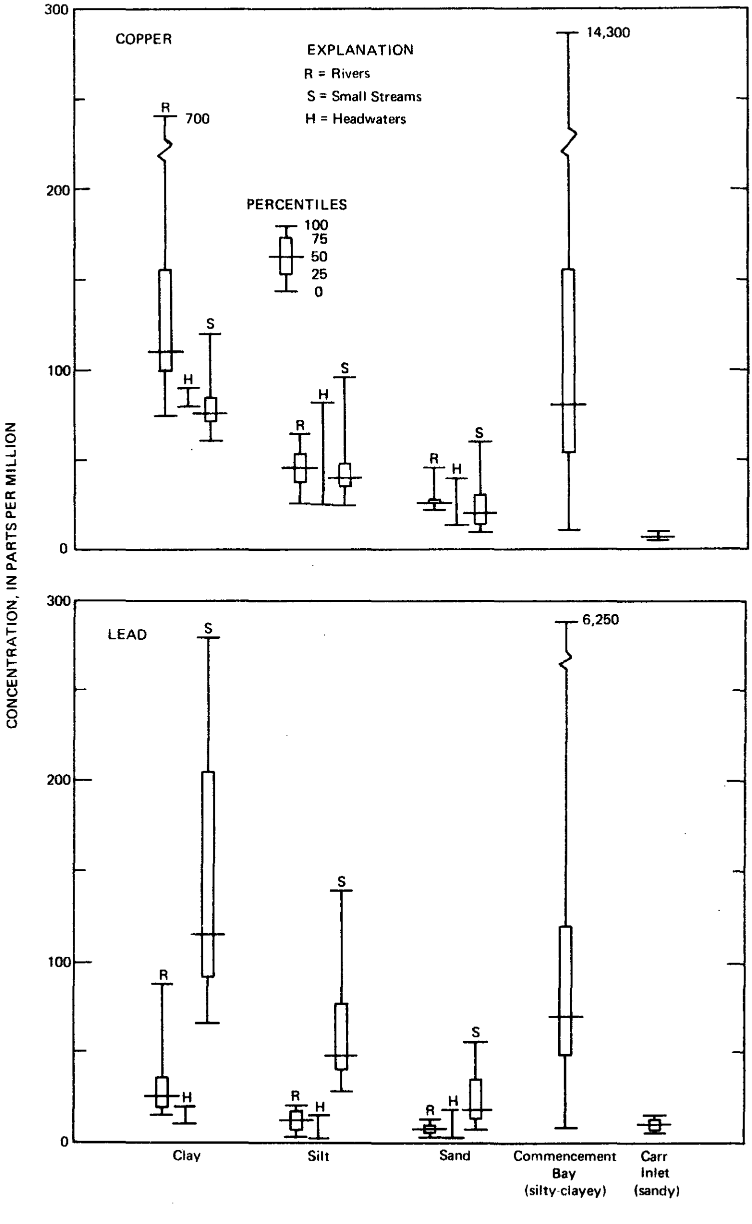

FIGURE 2. - - Copper and lead concentration in sediment from headwaters, Puyallup and White Rivers, small streams and two areas in Puget Sound.

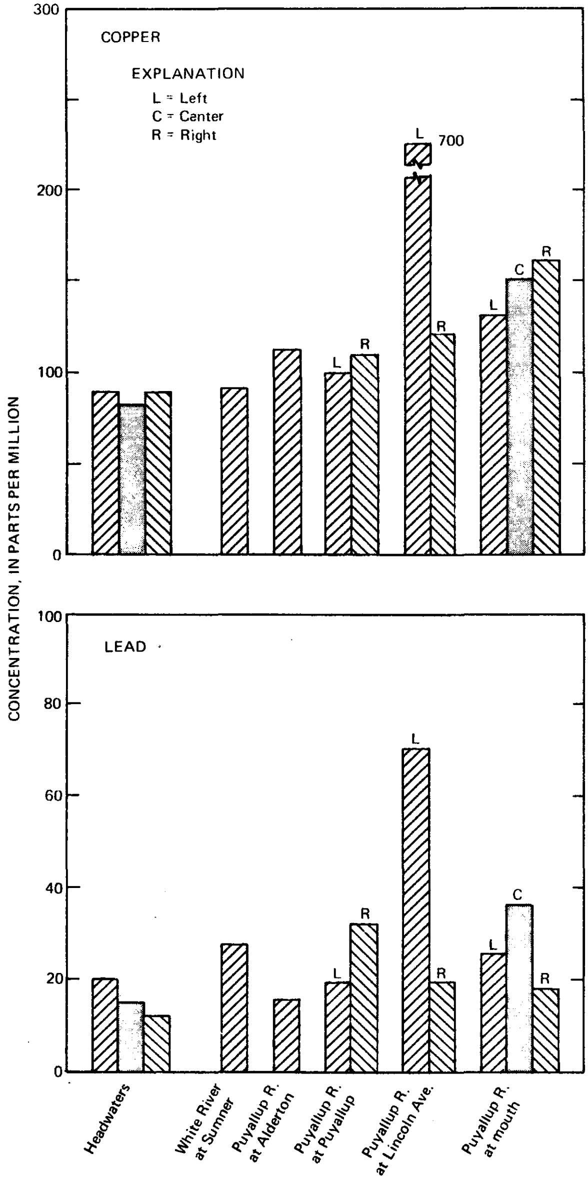

FIGURE 3. - - Copper and lead concentrations in the clay-size fraction of the White and Puyallup River bed sediments collected August 1983.

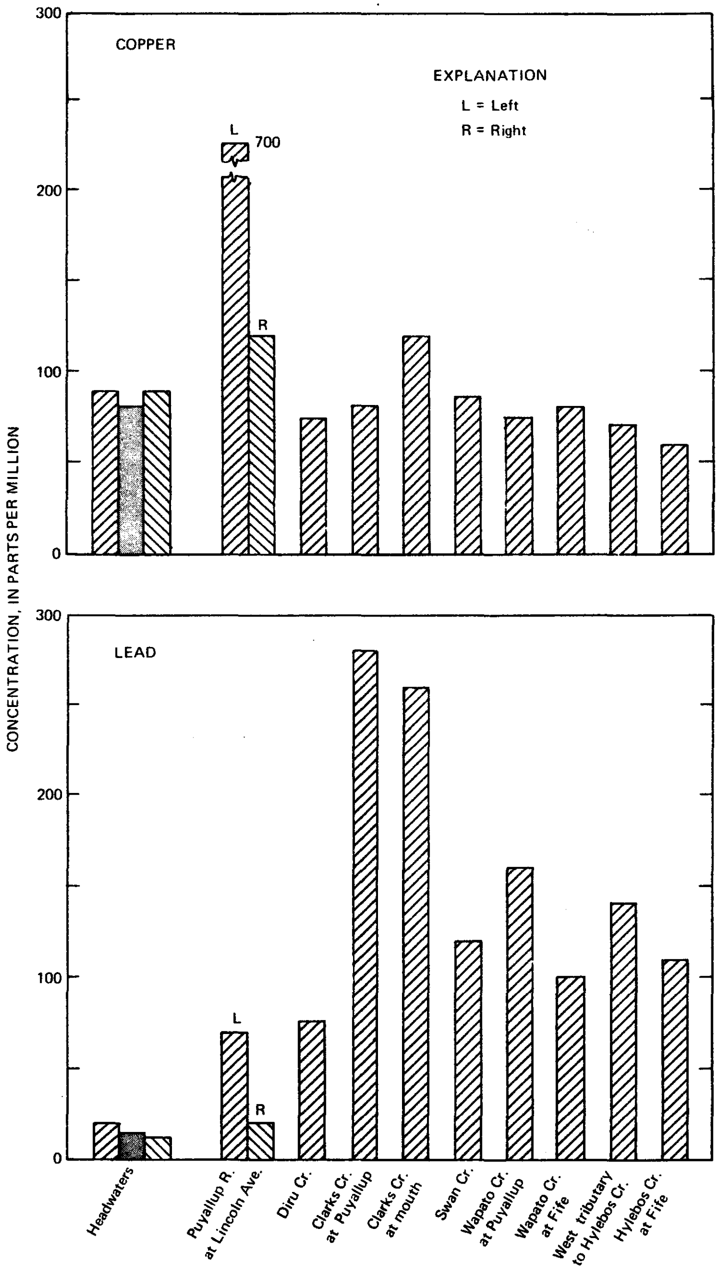

FIGURE 4. - - Copper and lead concentrations in the clay-size fraction of bed sediments collected from small streams August 1983.

in sediments from the headwaters. This sampling site is approximately 1,000 feet downstream from the discharge of a municipal wastewater treatment plant and 4,000 feet downstream from a major storm-water outfall, both located on the left bank of the river. The discharge plume from the treatment plant is often visible along the left bank.

Copper, and perhaps lead, concentrations in bed sediments collected near the mouth, about 7,500 feet downstream from the Lincoln Avenue sampling site, are somewhat greater than concentrations in samples collected at headwaters sites (fig. 3), but any effect of the treatment plant or other discharges to the lower Puyallup River on concentrations is clearly diminished. This may be a result of dilution by uncontaminated sediments contained in glacial meltwater from Mount Rainier. In April 1984, when the river carried little glacial meltwater, copper and lead concentrations (not shown) in sediments at the mouth near the left bank were elevated. Concentrations at other locations in the Puyallup River were similar to, or slightly larger than, concentrations in headwaters samples.

Copper concentrations in the clay-size fractions of bed-sediment samples collected in August 1983 from the small streams generally were not larger than concentrations in samples from the headwaters sites (fig. 4). However, lead concentrations in these samples were larger than concentrations in bed-sediment samples collected both at the headwaters sites and at sites on the lower Puyallup River (fig. 4). The larger lead concentrations in samples from the small streams could be caused by urban runoff, which typically contains elevated concentrations of lead (Galvin and Moore, 1982). The drainage areas of the small streams are entirely within the Puget lowlands, and therefore, they receive more urban runoff as a percentage of total flow than does the Puyallup River. Clarks Creek, where lead concentrations in bed sediments were higher than those at most other sites, receives storm-water drainage from many streets in and near the city of Puyallup.

<u>Comparison with Puget Sound sediments</u>

Copper and lead concentrations in bed-sediment samples collected from the Puyallup River and small streams during this study were compared with published (Tetra Tech, 1985) concentrations in surficial bottom sediments from Carr Inlet and Commencement Bay of Puget Sound (fig. 2). The samples from Carr Inlet, located about 10 miles southwest of Commencement Bay, were collected to obtain relatively uncontaminated Puget Sound bottom sediments. The samples from Commencement Bay were collected mostly along the southwest shoreline and in and near the waterways located at the southeast end of the bay. Some of the Commencement Bay sediments were highly contaminated (fig. 2).

A precise comparison cannot be made between copper and lead concentrations in the Puget Sound samples and those from the Puyallup Valley streams because 1) the Puget Sound samples were not separated into size classes prior to analysis, and 2) the analytical method for the Puget Sound sediments used a digestion procedure that, although rigorous, may not have resulted in a complete

dissolution of sediment particles (Tetra Tech, 1985). Although it is not possible to determine the magnitude of differences in concentration resulting from the different digestion procedures, the digestion procedures used for the Puget Sound sediments would yield concentrations equal to or less than those that would be obtained with the procedure used on Puyallup Valley stream sediments. The difficulty of comparing concentrations in fractionated and unfractionated samples can, however, be minimized. Although the Puget Sound sediments were not separated into size fractions prior to analysis, the particle-size distributions of samples were determined. Therefore, concentrations in Puget Sound samples that were composed mostly of one size class reasonably could be compared with concentrations in the same size fraction of samples analyzed in this study.

The bottom sediments collected in Carr Inlet were predominantly sand (87 percent ± 7 percent, mean ± standard deviation) and had lead and copper concentrations that were similar to or less than concentrations in the sand fractions of headwaters samples. Lead concentrations in the sand-fraction of bed sediments from the Puyallup River were similar to concentrations in samples from Carr Inlet (fig. 2). However, lead concentrations in the sand-fraction of a large percentage of bed-sediment samples from the small streams were larger than concentrations in Carr Inlet samples (fig. 2). Copper concentrations in Carr Inlet samples were generally smaller than concentrations in the sand-fraction of bed sediments collected from either the small streams or the Puyallup and White Rivers (fig. 2).

The mean silt-plus-clay content of the bottom sediments for different areas of Commencement Bay ranged from 20 to 88 percent (Tetra Tech, 1985). Most of these samples were collected in near-shore locations of suspected trace-metal contamination, and therefore may not represent typical Commencement Bay bottom sediments. Copper and lead concentrations were higher than in headwaters samples. Copper concentrations in a large percentage of Commencement Bay samples were similar to concentrations in the clay- and silt-size fractions of a large percentage of samples from the Puyallup and White Rivers and from the small streams. Concentrations of lead in the Commencement Bay samples were mostly higher than those in Puyallup River and White River bed sediments, but most were bracketed by concentrations in the clay- and silt-size classes of sediment samples from the small streams.

Summary and Conclusions

Bed sediments collected from the Puyallup and White Rivers and from seven small streams in the lower Puyallup valley were separated into sand-, silt-, and clay-size fractions and analyzed for copper and lead content. Concentrations were generally largest in the clay-size fractions of samples and smallest in the sand-size fractions. These concentrations were compared with concentrations in supposedly uncontaminated sediments from the headwaters of the streams and in sediments from Puget Sound.

Concentrations of copper and lead in the clay-size fraction of Puyallup and White River bed-sediment samples were larger than concentrations in this size-class fraction of headwaters sediment samples. Concentrations of copper in the river sediments were higher than those of bottom sediments of Carr Inlet, which are believed to be uncontaminated, but concentrations of lead were similar. Concentrations of copper in the river bed sediments were similar to those in bed sediments from suspected areas of contamination in Commencement Bay, but lead concentrations were smaller.

Concentrations of copper in all size classes of bed sediments from the small streams were similar to those in headwaters samples. However, concentrations of lead were larger. Concentrations of copper and lead in small-stream bed-sediment samples were larger than in Carr Inlet sediments but were similar to those for Commencement Bay.

The largest observed concentrations of copper and lead in the clay-size fraction of Puyallup River bed sediments were at points downstream from a municipal wastewater treatment plant and a major storm-water outfall. Lead, but not copper, concentrations in the clay-size fraction of bed sediments from the small streams in the urban and industrial part of the lower Puyallup valley were larger than concentrations in Puyallup River sediments. This is probably because the small streams receive more urban runoff, which contains lead, as a percentage of their total flow than does the Puyallup River.

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The Effect of the Duwamish River Plume on Horizontal Versus Vertical Transport of Dissolved and Particulate Trace Metals in Elliott Bay

Richard A. Feely, Anthony J. Paulson, Herbert C. Curl, Jr., and David A. Tennant*

Introduction

Major sources of pollution to Puget Sound are derived from municipal, industrial, and riverine sources in the urban embayments. A large fraction of the contaminants are particulate or quickly become attached to particles in the water column. If these particles are dense, they tend to settle out of the water column near the source; thus analysis of sediments within urban embayments can provide an indication of the level of contamination, and by proximity, of the probable source of contamination. The question remains, however, to what extent are the contaminants transported out of the embayments into the main basin of Puget Sound. In other words, to what degree is the incoming contamination localized, or Sound-wide in nature. In order to address this problem the Pacific Marine Environmental Laboratory of NOAA made a series of observations in Elliott Bay in April 1985, and again in January 1986, to quantitatively determine to what extent trace metal contaminants are leaving the bay and entering the main basin of Puget Sound.

The approach employed in this study was to map the distributions of water properties (salinity, suspended particulate matter and toxic trace metals) during a period of high river runoff (April 4-5, 1985) and during combined sewer overflow events (January 8-9, 1986) after heavy rainfall. Current meters and sediment traps were deployed in Elliott Bay south of the Pier 90 anchorage. The current meters provided a continuous record of salinity, temperature, and current velocity. The sediment trap samples allows for a calculation of vertical transport contaminants associated with particles.

Physical setting

Elliott Bay is situated on the eastern shore of Puget Sound adjacent to the metropolitan area of Seattle, Washington (Fig. 1). It is a deep embayment (>175 m) with a steep channel leading into the main basin of Puget Sound. Freshwater is added to the bay from the south by the West and East Duwamish Waterways,

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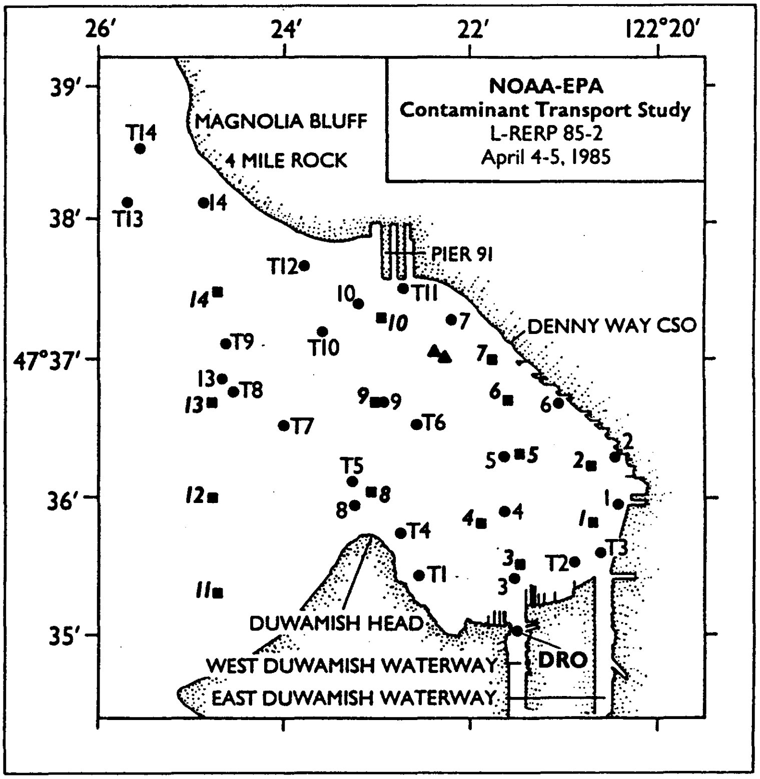

Fig. 1. Geographic setting of study area including station locations for the April, 1985 suspended matter and trace metal survey in Elliott Bay. The triangles show mooring locations.

with the majority of the flow (~80%) being carried by the West Duwamish Waterway (Stoner, 1972). The source water for the waterways is the Green River whose headwaters originate in the Cascade Mountains. At about river kilometer 20, the Green River is joined by the Black River and becomes the Duwamish River. At river kilometer 10, the Duwamish River empties into the dredged Duwamish Waterway, which is adjacent to the industrial area of Seattle. The annual sediment transport of the Duwamish River ranges from about 52,000 to 340,000 mt per year (Santos and Stoner, 1972).

During the two-week period preceding our 4-5 April survey flow rates in the Duwamish River exceeded 150% above the ten-year mean. The average flow rate for the 5-day period prior to the survey was 96 m^3/sec. At the beginning of the sampling effort on 4 April, the rains lessened to a drizzle (<0.1 inch/day) and the winds became light and variable.

Rainfall for the end of 1985 was much lower than normal. During the 8-9 January 1986 sampling period the Duwamish River flow was about half of the ten-year mean, or approximately 31 m^3/sec. About 2 inches of rain fell in a storm which occurred between 31 December

and 5 January. While this storm did not markedly increase Duwamish River flow, it did cause the combined sewer overflows (CSOs) to discharge significant quantities of runoff into Elliott Bay over the period from 3 through 9 January. For example, during the overflow event sampled on 8 January 1986 the Denny Way CSO discharged a total 16,800 m^3 into Elliott Bay and the Harbor Island CSO also discharged 417 m^3 into the West Duwamish Waterway several hours prior to sampling. The winds were from the south and southeast at speeds up to 29 m/sec during this survey period.

Sampling and Analytical Methods

Samples for total suspended matter (TSM), dissolved trace elements, and particle composition were collected in acid-cleaned bottles and filtered through preweighed, acid-cleaned filters (0.4 µm pore size, 37 mm Nuclepore filters). Shallow, high-resolution salinity and total suspended matter measurements were performed from the bow of a small boat with a battery-operated Montedoro-Whitney CTM-1 salinometer coupled with a Sea Tech. transmissometer. The data from these measurements were calibrated based on the discrete measurements from the water bottle samples. Sediment trap samples were obtained from moored arrays (Baker and Milburn, 1983). The lucite collection cylinders were cleaned in 6N HCl and then rinsed with deionized water before deployment.

Total elemental composition of the suspended matter was determined by X-ray primary- and secondary-emission spectrometry using the thin-film technique (Baker and Piper, 1976; Feely *et al.*, 1981, 1986; Holmes, 1981). A Kevex Model 7077-0700 X-ray energy spectrometer with a rhodium tube was used in the direct and secondary mode. Thin-film standards were prepared from U.S. Geological Survey Standard Rocks and NBS Standard Reference Materials. Dissolved trace metals were determined by atomic absorption spectroscopy following preconcentration by the flow-controlled ion exchange procedure of Paulson (1986).

Results and Interpretations

Salinity and total suspended matter distributions

The near-surface salinity distribution in April, 1985 was characterized by the large freshwater plumes emanating from the West and East Duwamish Waterways with smaller plumes emanating from CSOs along the Seattle waterfront area (Fig. 2). The plumes from the two waterways coalesced into a single distinct plume in Elliott Bay which was confined to the eastern and northern sections of the bay. This pattern suggests that the major freshwater plume traveled counterclockwise along the eastern shore of Elliott Bay and then westward along the northern shoreline, which is consistent with the current measurements (Curl *et al.*, 1987). The results of the high-resolution (0-2 m) sampling illustrate the extremely thin layering of the freshwater plume (Fig. 2). Surface salinities in the region east of the West Duwamish Waterway were less than 20°/₀₀; whereas below 1.5 m the salinities are all greater than 22°/₀₀. The inventory of freshwater over several depth intervals

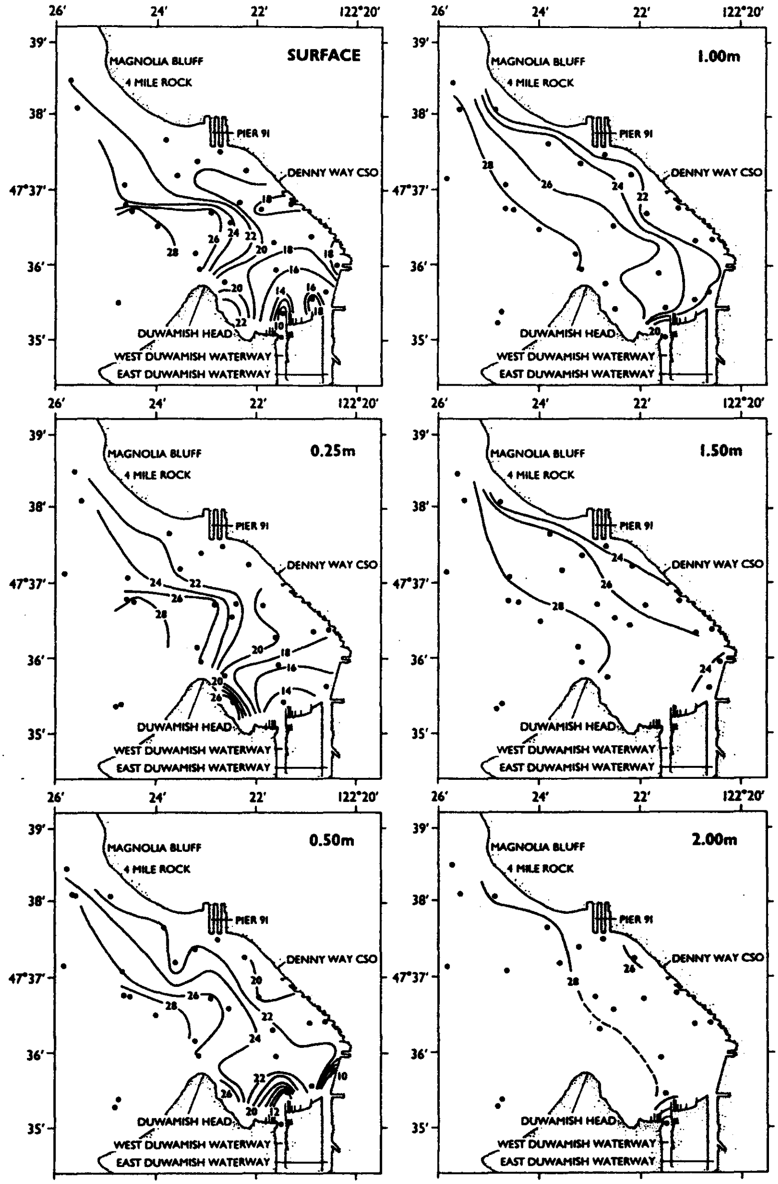

Fig. 2. Salinity distributions in upper 2 m of the Elliott Bay water column from high-resolution sampling (April 4-5, 1985).

in the upper 2 m was calculated for the April data (Table 1). This analysis indicated that approximately 51% of the freshwater resided in the upper 0.5 m while 74% resided in the upper 1 m. Based on the total inventory of freshwater in the upper 2 m (5.3×10^6 m^3)

and the freshwater flow of 96 m^3/sec, a residence time of 15 hours was calculated for freshwater in Elliott Bay.

Total suspended matter concentrations in Elliott Bay during April, 1985 showed large vertical gradients in near-surface waters, with distributional patterns reflecting the counterclockwise circulation pattern (Fig. 3). A regression of the April TSM concentrations versus salinity yielded a R^2 of 0.94, suggesting that TSM was essentially conservative in the bay under these hydrographic and

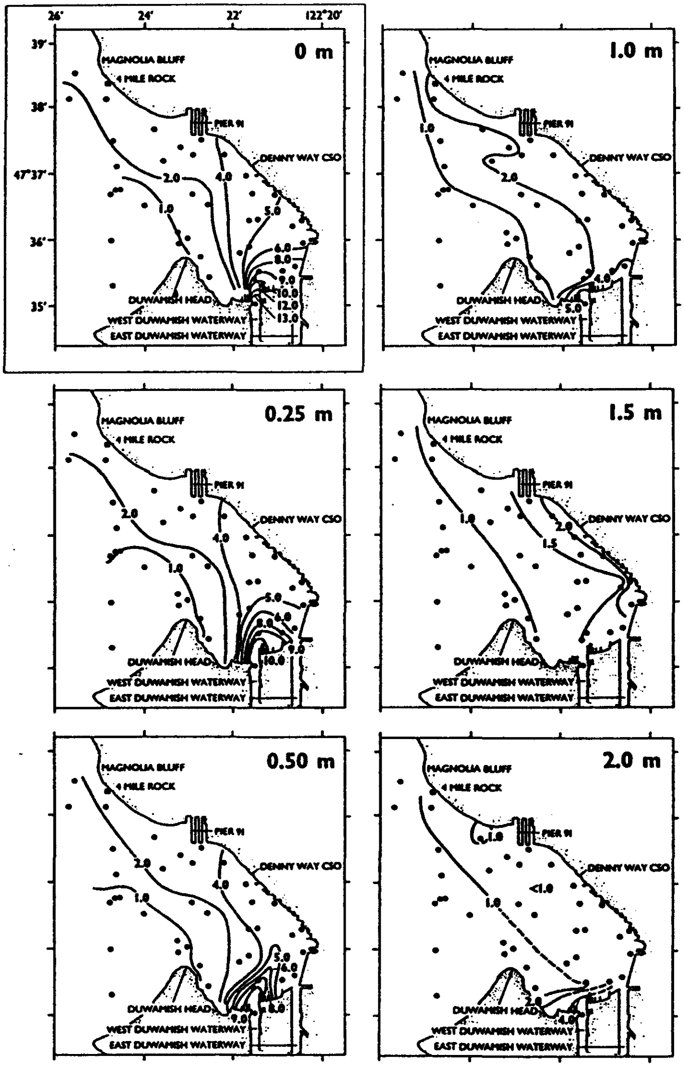

Fig. 3. Total suspended matter concentrations (mg/L) in upper 2 m of the Elliott Bay water column from high-resolution sampling (April 4-5, 1985).

Table 1. Inventory of freshwater and suspended matter in the upper 2 m of Elliott Bay. The percentage of the total is given in parentheses.

Depth Increment	Freshwater ($\times 10^6$ m^3)	Suspended matter (metric tons)
0 - 0.25 m	1.46 (28%)	16.9 (20%)
0.25 m - 0.5 m	1.21 (23%)	23.3 (28%)
0.50 - 1.0 m	1.23 (23%)	24.8 (30%)
1.0 - 1.5 m	0.93 (18%)	12.7 (15%)
1.5 - 2.0 m	0.45 (9%)	6.0 (7%)
TOTAL	5.28	84

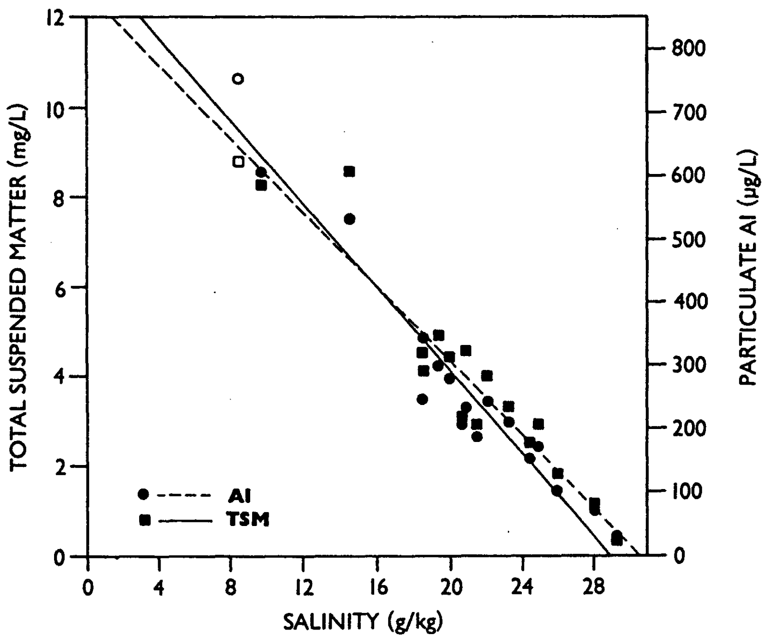

Fig. 4. Total suspended matter-salinity (■) and particulate Al-salinity (●) relationship for the near-surface samples from Elliott Bay. Open circles indicate West Duwamish Plume.

meteorological conditions (Fig. 4). Similar distributional patterns and correlations with salinity were also observed in the January data, although a secondary source of suspended matter was observed downstream of the Denny Way CSO.

Trace Metal Distributions

In general, dissolved and particulate trace metal distributions were controlled by physical mixing processes and followed the distribution of salinity. For example, dissolved and particulate Fe, Mn, and Pb distributions were similar to salinity and TSM distributional patterns, and exhibited linear relationships with salinity in near-surface waters (Fig. 5). The horizontal fluxes of these trace metals out of Elliott Bay were calculated from the distribution data coupled with freshwater inputs (Curl *et al.*, 1987; Paulson *et al.*, 1988a). The results are presented in Table 2. The horizontal flux of particulate Fe was calculated to be 99 g/sec, as compared with 0.67 g/sec for dissolved Fe. From this analysis it is concluded that particulate Fe constituted 99% of the total flux of Fe from Elliott Bay. Similarly, particulate Pb dominated the flux (>95%) of that element from the Bay. In contrast about two thirds of the Mn was transported out of Elliott

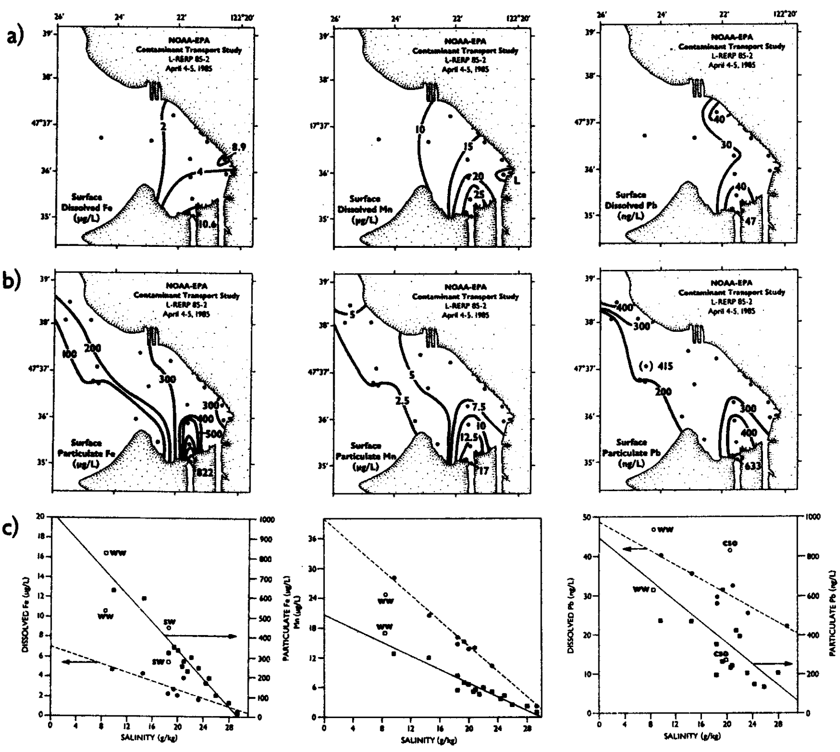

Fig. 5. Distribution of surface (a) dissolved Fe, Mn and Pb; (b) particulate Fe, Mn and Pb; and (c) dissolved Fe, Mn and Pb-salinity (●) and particulate Fe, Mn and Pb-salinity (■) relationship. Open circles indicate plume from West Duwamish Waterway (WW) and Seattle Waterfront (SW).

Table 2. Horizontal fluxes of dissolved and particulate trace metals and particulate vertical fluxes (in g/sec). Values in parentheses under the dissolved and particulate horizontal fluxes represent the percent of the total horizontal metal flux from both phases.

	Dissolved	Particulate		
	Horizontal	Horizontal	Vertical	Vertical/Horizontal (%)
Total Suspended Matter	---	1277 ±60	20	1.5
Fe	0.67 ±0.09 (0.7%)	99 ±5 (99%)	0.85	0.85
Mn	3.8 ±0.1 (66%)	2.0 ±0.1 (34%)	0.011	0.55
Pb	0.0048 ±0.0003 (5%)	0.086 ±0.009 (95%)	0.0020	2.3
Zn	0.57 ±0.05 (75%)	0.19 ±0.01 (25%)	---	---
Cu	0.077 ±0.008 (35%)	0.14 ±0.01 (65%)	0.0010	0.7

Bay in the dissolved form. When the vertical flux data from the sediment traps are extrapolated over the total area of Elliott Bay the horizontal fluxes can be compared with the vertical fluxes. The results of these calculations are also given in Table 2. For total suspended matter, Fe, Mn, and Pb, vertical fluxes constituted only about 0.5-2.3% of the horizontal fluxes. These results indicate that more than 95% of the trace metals in the surface plume are transported out of the Bay during high flow conditions.

Unlike the previous metals examined, the highest dissolved Cu and Zn concentrations were found in the surface waters of Elliott Bay near Harbor Island (Fig. 6). These observations may have been the result of geochemical desorption reactions off particles suspended in the buoyant plume, or temporal variability of the riverine source or sources other than the Duwamish Waterway. Although desorption and temporal variability in the Duwamish Waterway could account for some of the high Cu and Zn concentrations in the Bay, other data suggest that the advection from the northern shores of Harbor Island was responsible for these increases. During the January survey a plume containing dissolved Cu and Zn

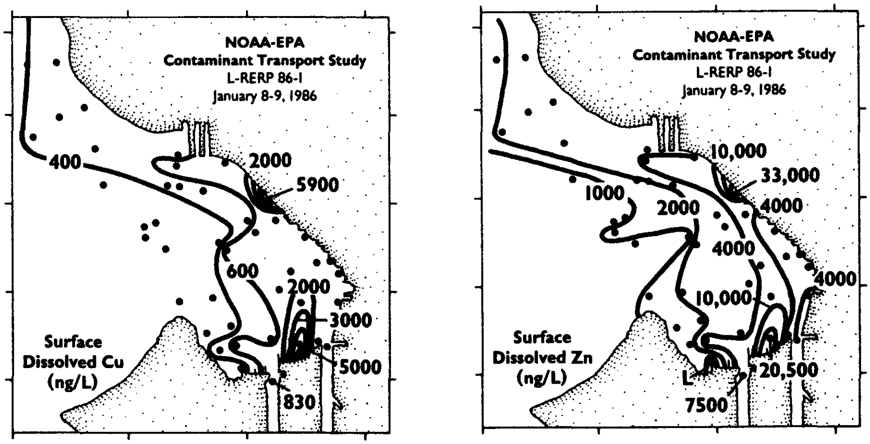

Fig. 6. Distribution of surface (a) dissolved Cu and (b) dissolved Zn from the January 8-9, 1986 survey.

concentrations of 5000 and 20,500 ng/L, respectively, was observed off the northern shores of Harbor Island (Fig. 6). The sediments off Harbor Island near shipbuilding facilities also exhibited high concentrations of Cu and Zn (Gamponia *et al.*, 1986). The fact that Cu and Zn are primary pollutants associated with shipbuilding activities and the fact that both Cu and Zn showed similar and unique distributions support the hypothesis that these distributions were the result of anthropogenic sources. Since dissolved Cu and Zn exhibited linear salinity relationships downstream of this source in the April, 1985 data set, horizontal transports can be calculated. While 75% of the total Zn was transported in the dissolved phase, the transport of dissolved Cu amounted to only 35% of the total flux (Table 2).

Elemental composition of the particulates

The elemental composition of the particulates in the surface layer of Elliott Bay is determined by the relative contributions of particulates from riverine, main basin and anthropogenic sources, by geochemical scavenging reactions, and by physical processes such as differential settling. The relative importance of these processes can be evaluated by comparing the elemental composition of particulate matter in Elliott Bay with that of the freshwater portion of the Duwamish River. Table 3 shows a summary of elemental composition data for the Duwamish River and Elliott Bay during different periods of low and high river flow. The data from the 1980 through 1984 periods are from Paulson *et al.* (in press). While the concentrations of Fe, Pb, and Zn in particulates sampled at the head of the Duwamish Waterway were nearly the same as those in the freshwater portion of the river, the concentrations of Cu and Mn in Duwamish Waterway particulate matter were 150% and 40% higher, respectively, than the river particulates. Although

Table 3. Elemental composition of suspended and settling particulates in Elliott Bay and the Duwamish River.

		Fe (wt%)	Mn (ppm)	Pb (ppm)	Zn (ppm)	Cu (ppm)	n
Green-Duwamish River		6.25[1]	1150[2]	45[2]	150[2]	42[2]	5
Suspended Sediments		±2.00	±332	±9	±84	±6	
(1980-1984; sal=0)		(n = 7)					
Head of West Duwamish Waterway		7.72	1595	59	137	106	1
Suspended Matter							
(April, 1985; sal=8.4)							
Elliott Bay		7.90	1700	86	183	113	14
Suspended Matter		±1.06	±88	±36	±27	±11	
(April, 1985; sal=10-26)	RSTD	13%	5%	43%	15%	10%	
Elliott Bay		4.25	553	100	--	52	1
Settling Particulates (6 m)							
(April, 1985)							
Elliott Bay[3]		6.91	4100	370	300	127	18
Suspended Matter		±2.00	±1700	±182	±85	±24	
(Feb, 1980)	RSTD	29%	41%	49%	28%	19%	

RSTD: Relative standard deviation
1) Massoth *et al.*, 1982
2) Paulson *et al.*, 1988
3) Feely *et al.*, 1983

anthropogenic inputs are a major source of Cu to the Duwamish Water, Mn is thought to originate from natural sources (Harper-Owes, 1983). The enrichment of Mn in suspended matter at the head of the Duwamish Waterway relative to riverine sources was probably a result of precipitation of dissolved Mn diffusing from sediments in the upper 10 km of the Duwamish Waterway. Enrichments of Mn, Pb and Zn were also observed in Elliott Bay particulates in 1980 during conditions of lower river flow (Table 3). The lack of enrichments of Mn, Pb, and Zn under the higher flow conditions observed in April, 1985 is consistent with the lack of scavenging of dissolved metals from solution as evidence by their conservative behavior in Elliott Bay. The short residence time of freshwater in Elliott Bay during this high flow condition may have prevented scavenging reactions from occurring to any appreciable extent within the near-surface plume.

Discussion

The flow conditions and geometry of Elliott Bay may limit the effectiveness of trace metal scavenging reactions or differential settling as potential mechanisms for concentrating trace metal contaminants in the Bay. In April, 1985, the loss of only 1.5% of the suspended matter at a time when the residence time of the particles in the surface plume was less than 1 day suggests that the loss rate by vertical settling processes was about 2% per day. Even during low flow conditions when the winds have deepened the surface plume, the residence time of surface water in Elliott Bay is not expected to exceed 10 days (Sillcox *et al.*, 1981). At a suspended matter loss rate of 2% per day, vertical loss rates from the near-surface plume are not expected to occur to any appreciable extent in Elliott Bay even during low flow conditions. This conclusion is consistent with the observations of Baker *et al.* (1983) who suggested that sedimentation in Elliott Bay was not directly maintained by suspended matter settling from the surface layer. The increase in suspended matter concentrations with increasing salinity in the bottom nepheloid layer of Elliott Bay indicates an advective input of suspended matter from the deep waters of the main basin of Puget Sound. The advected particles then settle to the bottom as a result of the lower current speed in the near-bottom waters of the embayment.

In the beginning of this paper we asked the question, "To what extent are contaminants in the surface plumes from the Duwamish River and CSOs in Elliott Bay localized?" The answer appears to be quite clear that under most low flow conditions the great majority of trace metal contaminants are transported out of Elliott Bay to add to the trace metal burden of the main basin of Puget Sound. This is a major reason why surface waters in the main basin are elevated in dissolved and particulate trace metal concentrations near the mouth of Elliott Bay (Paulson *et al.*, 1988b). It is also the reason, in part, why sediments in the main basin are enriched in trace metals relative to sediments further to the north (Romberg *et al.*, 1984). Some of the particulate pollutants may settle to the deep basin and enrich the local sediments, while others may return to the embayment as a consequence of estuarine flow. In either case, it is clear that the management policies that are employed for the control of pollutants in the Duwamish Waterway and Elliott Bay will have far-reaching effects on pollutant distributions in the main basin and other embayments of Puget Sound. Future monitoring efforts should be designed to determine the temporal variability of contaminant fluxes from the urban embayments.

Acknowledgments

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Contrasting Sources and Fates of Pb, Cu, Zn and Mn in the Main Basin of Puget Sound*

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Introduction

Trace metals in Puget Sound originate from oceanic, riverine erosional and atmospheric sources as well as direct discharges of municipal and industrial wastes (Romberg *et al.*, 1984). Quantification of these sources of trace metals to the Puget Sound system help to put the discharge rate of a specific source into a system-wide perspective. With this system-wide perspective, the overall impact of the development of Puget Sound can be evaluated by comparing the natural sources of these metals from riverine, erosional and oceanic sources with the anthropogenic inputs from municipal, industrial and atmospheric inputs. While riverine sources do not presently originate completely from natural weathering processes and not all atmospheric deposition is man-made, this general classification provides an initial insight into man's impact on an estuary. However, lack of knowledge of the partitioning of trace metals between the dissolved and particulate phase prevents scientists and managers from predicting whether a discharge will have a greater impact on the water column or the sediments. By constructing individual dissolved and particulate mass balances for the system, we can begin to understand how different sources will impact the concentrations of these metals in both the water column or the sediments. By comparing the sources and sinks of a specific phase (i.e. the dissolved phase), we can determine if geochemical reactions are progressing to an extent that will alter the fate of these metals discharged into this estuary.

Mass balance calculations for dissolved, particulate and total Pb, Cu, Zn and Mn for the years 1980-1983 were performed for the study area which included central and southern main basin and the urban bays of Seattle and Tacoma, WA. Advective, riverine, erosional, municipal and industrial sources were considered along with sources from atmospheric deposition and diffusion from the sediments. The

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sinks of trace metals included advective transport from the main basin and sedimentation.

Results

The results of the mass balance calculations for Pb, Cu, Zn and Mn are given in Table 1. The details of the calculations are given in Paulson *et al.* (in press) and only highlights are listed below:

1) The estimates of mass balances of metals were limited by uncertainties in the budgets of water and, especially, particulates.
2) Because of increased analytical sensitivity due to the use of clean techniques, riverine and oceanic concentrations reported in this work were much lower than those reported prior to the 1980's.
3) The concentrations of Pb, Cu and Zn in Lake Washington Ship Canal water and on its particulates were much higher than those of the Duwamish and Puyallup Rivers.
4) Little in known about the change in partitioning of contaminants in primary and secondary effluents directly discharged into the marine environment.
5) For most industrial discharges, trace metal data for the time period studied was only available from one NPDES screening required for renewal of 5-year permits.
6) The discharge of Pb, Cu and Zn from industrial inputs located in the Duwamish industrial area were comparable to those from the West Point sewage treatment plant.

Discussion

Lead. Municipal, industrial and atmospheric sources each contributed about 22% of the 109 mt/yr of total Pb added to the main basin (Table 1 and Fig. 1). The known sources of Pb in Puget Sound

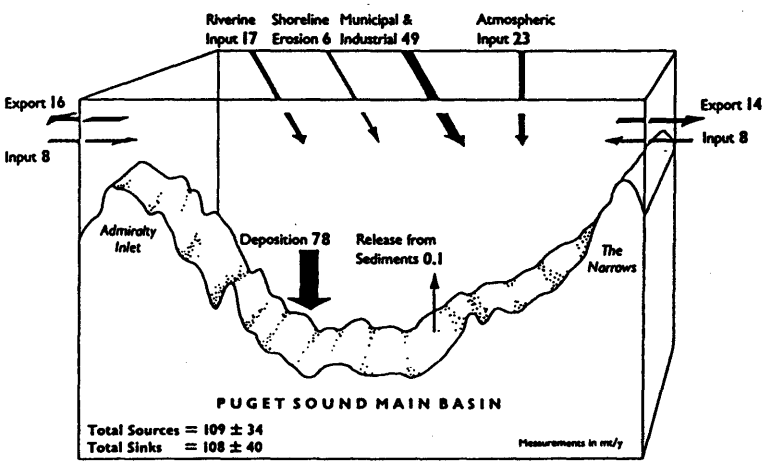

Fig. 1. Total Lead Budget for the Main Basin of Puget Sound (in metric tons/yr)

were balanced by the sedimentation (72%) and by advection from the main basin (28%). In contrast to other sources, greater than 95% of the 17 mt/yr of total Pb from riverine sources was in the particulate phase. Because of this large input of particulate riverine Pb, other sources, which are mostly anthropogenic, added only 55% of the 68 mt/yr of particulate Pb. It was found that the sinks of particulate Pb (sedimentation and advection) were 31 mt/yr greater than the amount of particulate Pb being added to the main basin of Puget Sound although this large difference is still within the 50% error of the budget calculations (Table 1). Because of the solubilization of atmospheric particulates and the prevalence of the dissolved Pb in industrial discharges, anthropogenic sources contributed about 85% of the 41 mt/yr of dissolved Pb added to Puget Sound (Fig. 2). However, only 12 mt/yr of dissolved Pb were found to be removed from the main basin. This significant difference between the sources and sinks of dissolved Pb indicates that 29 mt/yr of dissolved Pb was scavenged onto the particulate phase.

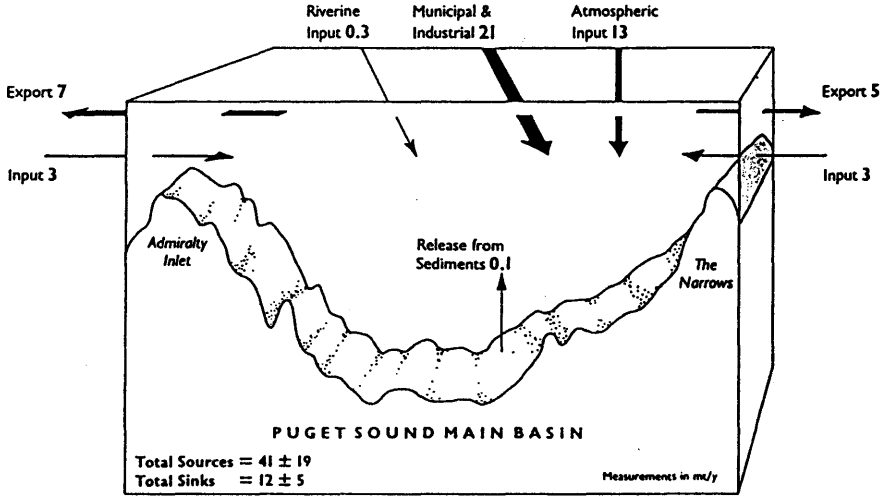

Fig. 2. Dissolved Lead Budget for the Main Basin of Puget Sound (in metric tons/yr)

Copper. Advection from the Strait of Juan de Fuca and South Puget Sound contributed 45% of the 222 mt/yr of Cu added to the main basin while riverine and erosional sources added 28% (Table 1 and Fig. 3). Municipal and industrial sources contributed about 11% each. The sinks of total Cu balanced the sources of total Cu within the errors of the budget calculations. About 40% of the total Cu remained within the sediments of Puget Sound while 60% was advected from the main basin. The combination of riverine and erosional sources were the more significant sources of particulate Cu (59% of the 97 mt/yr of particulate Cu) while the advective sources added 19%. Municipal, industrial and atmospheric inputs added about 23% of the total particulate Cu. The sources of particulate Cu were balanced by the removal by sedimentation (78%) or by advective transport (22%). This agreement between the sources and sinks of particulate Cu suggests that Cu in the main basin

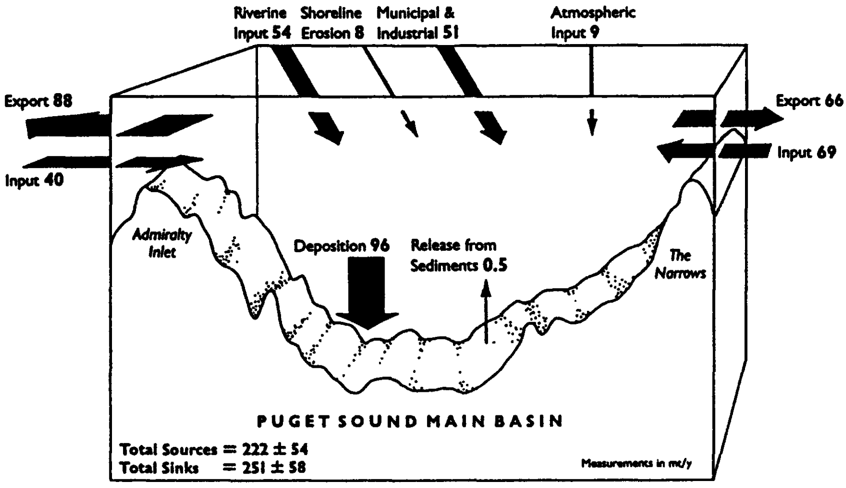

Fig. 3. Total Copper Budget for the Main Basin of Puget Sound (in metric tons/yr)

did not participate in adsorption reactions to an extent that we were able to detect (i.e. Cu was conservative within the 50% error of the analysis). Advection contributed about 66% of the 125 mt/yr of dissolved Cu while riverine sources added 4% of the dissolved Cu to the main basin (Fig. 4). The configuration of the box for these mass balances overstated the importance of the advective term in that the southern boundary of the box (the Narrows) is connected a terminal basin (South Puget Sound). The fact that the flux of dissolved Cu advected across the Narrows from the main basin was equal to the amount advected from South Puget Sound suggests that main basin water is merely recycled through South Puget Sound.

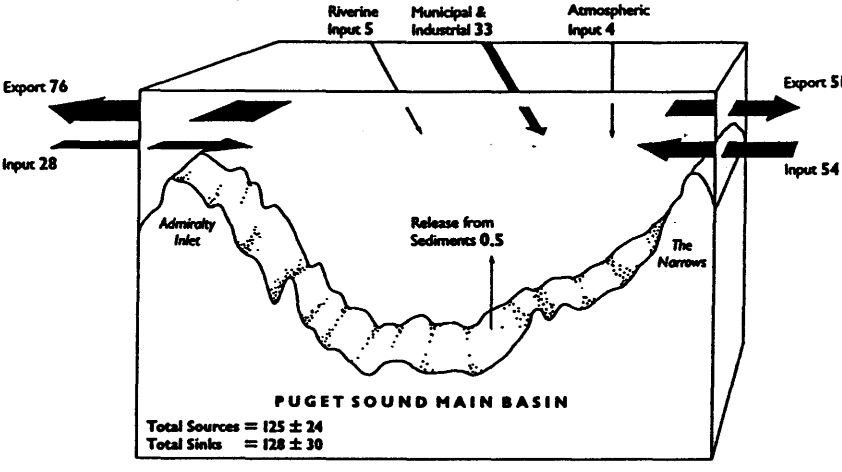

Fig. 4. Dissolved Copper Budget for the Main Basin of Puget Sound (in metric tons/yr)

This would suggest that baseline dissolved Cu concentrations in South Puget Sound are controlled by inputs to the main basin. The impact of this recycling can only be evaluated using a model which includes movement of water through the southern main basin such as that described by Cokelet *et al.* (1984). Municipal, industrial and atmospheric sources added 30% of the dissolved Cu inputs. The diffusion of Cu from the sediment porewaters did not seem to be a significant source of dissolved Cu. Advection of dissolved Cu from the main basin, the only sink for dissolved Cu, balanced the sources within the 20% errors of the budgets (Table 1). The smaller errors of dissolved Cu budget compared to the particulate Cu budget offered the better sensitivity to demonstrate the quasi-conservative nature of Cu within the boundaries of this box model.

Zinc. The sources and sinks of Zn were similar to those of Cu. Advective sources contributed 38% of the 369 mt/yr of Zn added to the main basin while the combination of riverine and erosional sources contributed 32% (Table 1 and Fig. 5). Municipal and industrial sources each contributed 14% of the Zn. Atmospheric deposition and diffusion from the sediments contributed less than 2%. Like Cu, the advective sources were a more important sources of dissolved Zn (53% of the 192 mt/yr dissolved Zn) than particulate Zn (22% of the 177 mt/yr particulate Zn). In contrast, riverine and erosional sources added 59% of the total particulate Zn but only 7% of the dissolved Zn. Like Cu, municipal and industrial sources seemed to a more important source of dissolved Zn (37% of dissolved Zn) than of particulate Zn (17% of the particulate Zn). The sinks of Zn were also similar to those of Cu. About 45% of the total Zn remained within the sediments of the main basin Puget Sound while 55% was advected from the main basin (47% as dissolved

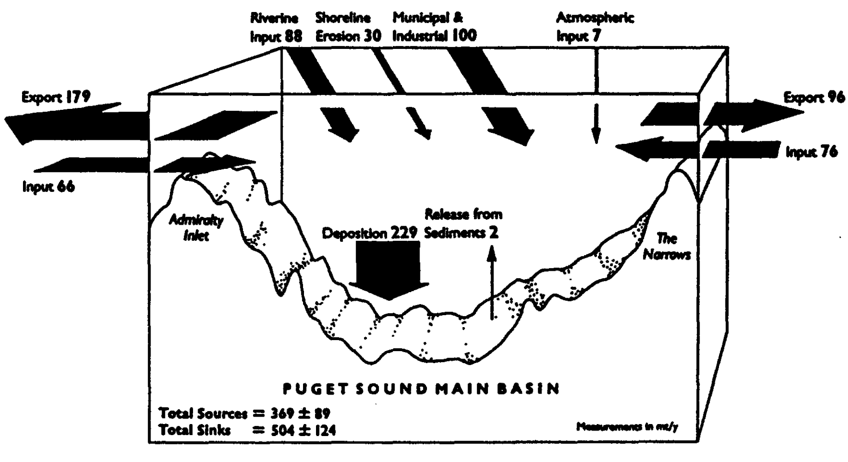

Fig. 5. Total Zinc Budget for the Main Basin of Puget Sound (in metric tons/yr)

Zn and 7% as particulate Zn). The sources of particulate Zn are comparable to the sinks within the large 40% error of the budget calculation. The sources of dissolved Zn were also comparable to the advection of Zn from the main basin within the 25% error. These observation suggest that Zn is also quasi-conservative within the main basin of Puget Sound.

Manganese. Diffusion of dissolved Mn from the sediments contributed 77% of the 9900 mt/yr of Mn added to the main basin of Puget Sound (Table 1). However, less than 10% of the dissolved Mn added to the main basin was advected from the main basin. This substantial loss of dissolved Mn was a result of the rapid formation of particulate Mn from the oxidative precipitation of dissolved Mn (Feely *et al.*, 1983; 1986). This particulate Mn then settled to the bottom sediments, where it again redissolved due to reducing conditions in the sediments. This rapid cycling of Mn between the oxidative precipitation and reductive dissolution cycles provides a large amount of oxide surfaces for metals which have a high scavenging affinity for manganese oxide surfaces such as Pb (Paulson *et al.*, submitted).

Conclusion

Construction of individual dissolved and particulate mass balances for trace metals allows one to evaluate the impacts of changing anthropogenic inputs on both the water column and the sediments and the occurrence of scavenging reactions. Municipal, industrial and atmospheric inputs added 85% of the dissolved Pb discharged to the main basin. However, comparison of the sources and sinks of dissolved Pb indicated that 75% of the dissolved Pb added to the main basin was scavenged onto particulates. This scavenging of anthropogenic dissolved Pb tended to result in the retention of anthropogenic Pb in the sediments of the main basin of Puget Sound. The net effect of this scavenging and the discharge of particulate Pb from rivers and anthropogenic sources was the sedimentation within the main basin of 72% of the total Pb input. The sources and sinks of dissolved Cu and Zn were comparable, which indicated their quasi-conservative geochemical nature. Apparently, the fates of Cu and Zn were mainly determined by their partitioning between the dissolved and particulate phases in different source discharges. The nature of discharges to the main basin of Puget Sound resulted in only 40% of the total Cu and Zn being retained in the main basin sediments while 60% was advected from the system. Diffusion of dissolved Mn from reducing sediments and its subsequent oxidative precipitation onto particles controlled the fate of Mn.

Knowledge of the geochemical behavior of these trace metals in the main basin could help environmental managers and regulators minimize the impacts of anthropogenic inputs at the lowest cost to society. For example, this research could benefit a program whose goal is to reduce the concentration of metals in marine sediments. Because of the extensive scavenging of dissolved Pb from anthropogenic sources, all Pb inputs would need to be reduced while only particulate Cu and Zn discharges would need to be controlled

because of their quasi-conservative behavior. Many economic and regulatory actions have already occurred in the Puget Sound basin since 1983 which will result in the reduction of trace metal discharges to the main basin. The decrease in the content of Pb in gasoline has already resulted in decreased rates of atmospheric deposition. The closing of the Tacoma and Seattle smelters and the economic demise of Puget Sound shipbuilding facilities will result in lower discharge rates of metals in our urban embayments. Even the hardening of drinking water by the Seattle Water Department has resulted in decreased discharge of some metals from METRO's municipal sewage treatment plants. The regulatory requirements to implement secondary treatment will further decrease discharge rates of trace metals from municipal sources throughout Puget Sound, especially those in the particulate phase. The hypotheses put forth by this work will be able to be tested in the next decade when the effects of these actions have had their impact on the concentrations of metals in the water column and sediments. The use of this trace metal mass balance approach for management purposes would benefit from further research that would decrease the uncertainties in the budgets of water and, especially, sediments which form the foundation of these trace metal budgets.

Acknowledgments

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Table 1. Known sources and sinks of total, dissolved and particulate Mn, Pb, Cu and Zn for the main basin of Puget Sound (metric tons per year).

Sources	Pb			Cu			Zn			Mn		
	T	D	P	T	D	P	T	D	P	T	D	P
Advection from:												
SJF	7.5	3.0	4.5	40	28	13	66	36	30	303	66	236
	±5.4	±3.0	±4.5	±15	±7	±13	±36	±17	±30	±237	±23	±236
SPS	7.5	3.3	4.2	69	54	5	76	65	11	910	227	682
	±4.8	±3.3	±4.2	±20	±19	±5	±25	±23	±11	±684	±61	±682
	15	6	9	100	82	18	141	101	40	1212	293	918
	±7	±4	±6	±25	±21	±14	43	±29	±3	±723	±65	±722
Riverine	17	0.3	16	54	5	49	88	13	75	632	117	516
	±12	±0.2	±12	±44	±1	±44	±58	±3	±58	±376	±31	±375
Erosional	6	--	6	8	--	8	30	--	30	266	--	266
	±6		±6	±8		±8	±30		±3	±266		±266
Municipal	24	6	17	26	14	12	50	29	22	51	46	5
	±14	±3	±5	±7	±4	±3	±13	±10	±9	±10	±10	±2
Industrial	25	15	10	25	19	6	50	41	8	93	51	54
	±15	±12	±7	±13	±11	±3	±40	±35	±5	±69	±37	±48
Diffusive	0.1	0.1	--	0.5	0.5	--	1.5	1.5	--	7615	7615	--
	±0.1	±0.1		±0.5	±0.5		±1.5	±1.5		±4600	±4600	
Atmospheric	23	13.3	9.7	9	4	5	7	1.5	2	2.7	1.3	1.4
	±23	±13.3	±9.7	±9	±4	±5	±7	±1.5	±2	±2.7	±1.3	±1.4
TOTAL INPUTS	109	41	68	222	125	97	369	192	177	9873	8123	1760
(Uncertainty)	±34	±19	±19	±54	±24	±47	±89	±47	73	±4650	±4600	±857

Table 1. (cont.)

	Pb			Cu			Zn			Mn		
	T	D	P	T	D	P	T	D	P	T	D	P
Sinks												
Advection to:												
SJF	15.8	7.4	8.4	88	76	12	179	155	24	±764	254	509
	±9.7	±4.8	±8.4	±27	±24	±12	±54	±50	±24	±536	±167	±509
SPS	14.2	4.8	9.4	66	51	15	96	82	14	1110	564	547
	±9.8	±2.7	±9.4	±23	±18	±5	±30	±26	±14	±994	±830	±547
	30	12	18	155	128	27	275	236	37	1875	819	1056
	±14	±5	±13	±36	±30	±19	±63	±56	±27	±1129	±847	±750
Sedimentation	78	--	78	96	--	96	229	0	229	7690	--	7690
	±37		±37	±45		±45	±108		±108	±3500		±3500
TOTAL OUTPUTS	108	12	96	251	128	123	504	237	266	9565	819	8746
(Uncertainty)	±40	±5	±39	±58	±30	±49	±124	±56	±111	±4650	±847	3589

T = TOTAL; D = DISSOLVED; P = PARTICULATE; SJF = Strait of Juan de Fuca and SPS = South Puget Sound.
Uncertainty expressed as estimates of one standard deviation.

Retention of Organic Pollutants in Puget Sound

Paulette P. Murphy, Timothy S. Bates, Herbert C. Curl, Jr., Richard A. Feely and R. Scott Burger*

Abstract

Hydrocarbon concentrations were measured on suspended particulates and on surficial marine sediments in the urban fjord-like estuary of Puget Sound, Washington. These data were combined with sediment deposition rates, suspended particulate concentrations and circulation data to assess hydrocarbon distributions and fates. Evaluation of major sinks for petroleum hydrocarbons (UCM) and polycyclic aromatic hydrocarbons (PAH) in the urban estuary indicates that >93% of the hydrocarbons which are associated with suspended particulates in the main basin of Puget Sound are deposited in the estuarine sediments. Approximately 63% of the PAH and 100% of the UCM associated with particles in the main basin settle directly to the sediments. The remainder is carried to the main basin sediments via horizontal transport from other areas. Trends in PAH ratios are used to identify major sources of PAH. Estimated sources of PAH are balanced by the estimated sinks.

Introduction

One of the hallmarks of modern civilization is increased hydrocarbon consumption. Recent studies by Malins *et al.* (1984) and others have shown, however, that elevated hydrocarbon levels in estuarine waters and sediments can have adverse effects on marine life. Hydrocarbons enter an estuary via atmospheric deposition, river runoff, and municipal and industrial effluents, and tend to be associated with particles. If these hydrocarbon-bound particles are large and settle quickly, it is expected that a large fraction of the hydrocarbons discharged into an estuary would remain there; on the other hand, if the particles remain suspended and circulate with the water, the hydrocarbons may be removed from the estuary with outflowing water. Also, particle-bound hydrocarbons may settle from main basin surface waters to main basin sediments (direct vertical transport) or may be transported to main basin sediments from other areas by bottom currents (horizontal transport). Understanding the transport and ultimate fate of hydrocarbons in marine systems is important to assessing and predicting the local and distal impact of human activity on the marine environment.

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This study focuses on two hydrocarbon classes: polycyclic aromatic hydrocarbons (PAH) and an unresolved complex mixture (UCM). PAH compounds are produced by the combustion of organic matter, and in Puget Sound sediments derive principally from combustion of coal, oil, wood, and gasoline. They enter the estuary via direct atmospheric deposition or via runoff/discharge processes. Of the nine combustion PAH compounds we quantify, several, for example benzo(a)pyrene, are known carcinogens (Arcos and Argus, 1974). The other hydrocarbon class investigated, the unresolved complex mixture (UCM), is a measure of uncombusted petroleum hydrocarbons. It is a mixture of cyclic and branched chain molecules and elutes from gas chromatographic columns as a "hump" (Blumer *et al.*, 1970). Straight-chained aliphatic hydrocarbons have not been quantified in this study since their concentrations are seasonally dependent on biological activity in the water. The input of PAH and UCM to Puget Sound, on the other hand, is fairly constant throughout the year (Bates *et al.*, 1984).

Hydrocarbon Sinks

The particle-bound hydrocarbons entering Puget Sound have two ultimate reservoirs, or sinks. They can 1) settle, becoming buried and retained in marine sediments or 2) travel out of the estuary altogether, carried by outflowing currents into the Straits of Juan de Fuca.

Main basin sediments were investigated as a sink for particle-bound hydrocarbons using 19 surface sediment samples. Analysis for grain size and hydrocarbons showed a linear correlation between the two parameters. Grain size appears to largely determine the PAH and UCM concentrations on particles in the main basin of Puget Sound, and can be used to infer the hydrocarbon concentration on sediments of different type. Accumulation rates for sediments of different types (Romberg *et al.*, 1984) were used to calculate the accumulation rates for PAH and UCM in Puget Sound. 1600 ± 1100 kg PAH and 210,000 ± 150,000 kg UCM accumulate annually in the main basin. If Elliott and Commencement Bays are included, the annual accumulation is approximately 14% higher for PAH and 13% higher for UCM. An accurate assessment of sedimentation rates in these two embayments is difficult because dredging and landfill operations disturb the sediment record.

The other major sink for particle-bound hydrocarbons is transport across Admiralty Inlet with the water flowing seaward out of Puget Sound. Using a simple model for circulation based on the refluxing hypothesis (Ebbesmeyer and Barnes, 1980; Cannon and Ebbesmeyer, 1978) and ignoring particle settling in the sill zone, we can estimate the maximum amount of particle-bound hydrocarbon transported out of the estuary. This flux estimate is based on particle concentrations inside and outside the sill, hydrocarbon concentrations on those particles, and water transport rates across the sill. These quantities are derived, respectively, from transmissometer measurements, analysis of sediment trap particles, and the theoretical model of Cokelet *et al.* (1984). The maximum net transport out of Puget Sound is estimated to be 100 kg/yr for PAH and 16,000 kg/yr for UCM.

Of the two hydrocarbon sinks considered, sedimentation accounts for a minimum of 94% and 93% of the PAH and UCM, respectively, removed from main basin waters; transport out of the estuary at Admiralty removes a maximum of 6% and 7% of PAH and UCM, respectively.

Transport Process

The transport pathways to main basin sediments for the largely anthropogenic, surface-derived PAH and UCM are 1) direct settling of particle-bound hydrocarbons from the surface (vertical transport) and 2) transport of particle-bound hydrocarbons into the main basin from other areas of deposition (horizontal transport). An evaluation of the relative importance of vertical transport is possible by comparing the mass of hydrocarbons falling through the 100-meter horizon in one year with the annual accumulation of hydrocarbons in the sediments.

Vertical transport of particles and particle-bound hydrocarbons were evaluated using data from 25 sediment traps placed throughout Puget Sound, all at 100-meter depth. Each trap collected settling particles for at least three months. The collected particles were analyzed for PAH and UCM, and the mean fluxes of particles, particle-bound PAH, and particle-bound UCM through the 100-meter horizon were calculated. The values are 2.9 ± 1.5 g particles/m^2/day, 5.2 ± 3.1 μg particle-bound PAH/m^2/day, and 1100 ± 800 μg particle-bound UCM/m^2/day. Accumulation of hydrocarbons settling to the 100 m horizon can be calculated by multiplying the area of Puget Sound at the 100-meter horizon by hydrocarbon flux. A minimum of $5.7 \pm 2.9 \times 10^8$ kg/yr particles, 1000 ± 600 kg/yr PAH, and $220 \pm 160 \times 10^3$ kg/yr UCM fall through the 100 m horizon.

Approximately 27% of the particulate matter which accumulates in the sediments arrives via direct settling through the 100-meter horizon. The remainder is inferred to be transported to the main basin sediments by bottom currents (i.e. horizontal transport). Sources of this material could be resuspended sediments transported from another location, bluff erosion, and submarine slumping. Although 27% of the particles accumulating in the main basin arrive via vertical transport, 63% of the particle-bound PAH and 100% of the particle-bound UCM settle directly to the sediments from the surface waters. These data imply that the concentration of hydrocarbons on vertically-transported particles is greater than that found on horizontally-transported particles.

Direct vertical transport is the predominant mechanism for transporting particle-bound hydrocarbons to main basin sediments.

PAH Budget

Adequate quantitative source information was available for construction of a PAH budget, but not a UCM budget, for Puget Sound. The estimated sources of PAH approximately balance our estimated sources, although all of these numbers have large uncertainties.

Sources kg/yr		References
240	West Point municipal waste water	Barrick (1982)
160	Other municipal waste water discharging directly to Puget Sound	Murphy *et al.* (1988)
270	Atmospheric deposition (wet and dry) average of urban, rural values	Prahl *et al.* (1984)
40	Elliott Bay storm drains	Murphy *et al.* (1988)
?	Other Elliott Bay sources	
190	Duwamish River (lower estimate)	Murphy *et al.* (1988)
300	Whidbey Basin (upper estimate)	Murphy *et al.* (1988)
300	Other horizontal transport, e.g. Puyallup River, transport from inlets (lower estimate)	Murphy *et al.* (1988)
?	Other sources	
1500		

Sinks kg/yr		References
1600 ± 1100	Sediment deposition in main basin	Murphy *et al.* (1988)
100	Transport out of estuary (upper estimate)	Murphy *et al.* (1988)
57	Elliott Bay sediments (estimate)	Murphy *et al.* (1988)
170	Commencement Bay sediment (estimate)	Murphy *et al.* (1988)
?	Other inlets	
?	Transport	
1900		

Conclusions

1) The main basin sediments of Puget Sound serve as a trap for hydrocarbons released to the estuary. Over 93% of the hydrocarbons which enter Puget Sound are deposited in the sediments.

2) 63% of the PAH and 100% of the UCM settle directly from surface waters; the other 37% of PAH is deposited in the main basin via horizontal transport from other locales.

3) Our estimates of PAH sinks can be balanced by our estimates of PAH sources.

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Summary Statement

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The papers in this session make a significant contribution to our understanding of sources and fates of toxic chemicals in Puget Sound. This knowledge of the geochemical behavior of toxic chemicals in the main basin should help environmental managers and regulators minimize impacts of the lowest cost to society.

The first paper describes a recent effort by the Puget Sound Estuary Program to develop standard protocols for many of the field and laboratory procedures used in studying Puget Sound. These protocols should be used by all organizations that collect data in Puget Sound so that comparable high quality data are produced. Presently, there are protocols for station positioning, sampling, and analysis of environmental samples for chemical contaminants, sediment bioassays, microbiology, and fish pathology. The development of the protocols involved a consensus-building process with local producers and users of the data participating in a workshop where the draft protocols were discussed. The protocols will undoubtedly increase the quality and comparability of information collected from Puget Sound.

The second paper presents an overview concerning the fate and effects of tributyltin (TBT) in the marine environment. The concentrations of TBT in restricted areas of marine waters could reach levels known to be toxic to marine life. In the past, TBT has been used in antifouling paints, but recent government regulations are restricting the use of TBT in antifouling paints, wood preservatives, and biocides. The fate of TBT in marine waters is to break down into lower molecular compounds that are less toxic. Biodegradation half-life for TBT is on the order of weeks. Uptake of TBT on particles may be the major removal mechanism for dissolved TBT. The bioavailability and toxicity of TBT bound to sediment is greatly reduced over the soluble form. Because of intense interest in TBT, there continues to be extensive research which should provide data needed to management risk of TBT in Puget Sound.

The third paper presents the development and application of protocols for butyltin compounds in sediments and tissues from Puget Sound. Samples are solvent extracted, derivatized, cleaned up on a chromatographic column then quantified by GC-MS. Surface sediment samples and English sole were collected from several locations in Puget Sound. Detectable concentrations of butyltins were found in sediment and fish liver tissue collected in industrial harbors.

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The fourth paper presents a mathematical model for predicting the amount of metal adsorbed on particles and the concentration in solution for a mixture of freshwater and seawater. The model has application in predicting the fate of metals that enter Puget Sound via rivers and outfalls. The model qualitatively predicts desorption behavior in the Duwamish River estuary for manganese, cadmium, and copper.

The fifth paper presents data on the concentrations of copper and lead in Puyallup Valley streambed sediments. Bed sediments were separated into sand-, silt-, and clay-size fractions. The concentrations of copper and lead were generally largest in the clay-size fraction. The largest observed concentrations of these metals in the Puyallup River were downstream from a waste-water outfall. Bed sediments from the small streams in the urban and industrial part of the lower valley were elevated with lead, probably from urban runoff.

The sixth paper describes the transport of metals through Elliott Bay. Metals that enter from the Duwamish River, Harbor Island, and the Denny Way CSO rapidly move out of Elliott Bay in a counterclockwise direction. The residence time of the surface layer is on the order of a few days and only a few percent of the suspended matter are lost from the water column in Elliott Bay.

The last two papers of this session present results from sources and fates of metals and hydrocarbons in the main basin of Puget Sound, respectively. For the metals, lead has the greater influence from anthropogenic sources with 22% of the total lead input from atmospheric deposition. The majority of dissolved and particulate lead is removed by sedimentation. Copper and zinc have significant anthropogenic source through municipal and industrial waste-water outfalls. However, these two metals are removed by sedimentation to a lesser extent than lead. The hydrocarbons are associated with the suspended particles in the water column of the main basin. About 93% of the hydrocarbons accumulate in the fine-grain sediments of the main basin with the remaining 7% transported out of the basin. Waste-water outfalls and atmospheric deposition are the major anthropogenic sources of PAH. Rivers and transport of PAH from other basins are also significant sources.

INTENSIVE-EXPENSIVE SURVEYS

WHAT HAVE WE LEARNED FROM THEM?

John Armstrong,
U.S. Environmental Protection Agency
Session Chair

INTRODUCTORY STATEMENT

John W. Armstrong*

Over the past fifteen years there have been a substantial number of large-scale field studies or surveys conducted throughout Puget Sound. Many of these surveys gathered large amounts of biological, chemical and physical information from the Sound. The surveys were conducted for a variety of purposes, such as to:

- Determine or monitor the effects of major discharges to the Sound,
- Establish baseline conditions in parts of the Sound in order to evaluate damages due to oil spills or other catastrophic events,
- Predict the effects of increased population growth and pollutant discharge to large areas of the Sound,
- Determine the best location for new outfalls,
- Evaluate conditions of, and pollutant sources to, our urbanized embayments, and
- Conduct reconnaissance level surveys to identify potential environmental problems in relatively poorly studied areas of Puget Sound.

A question we might ask ourselves is whether these intensive/expensive ($500,000 to over $1,000,000 for many of these studies) surveys have been a cost effective way to evaluate conditions and make decisions concerning Puget Sound. Specifically,are the more recent studies benefiting from the earlier work? Each successive survey includes some new methods, tests or measurements which

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haven't been attempted before. Some of these new approaches will be viewed as successes in assisting us make decisions about Puget Sound, while other tests or measurements will not be considered worthwhile. In order to wisely use our limited resources in better understanding and managing Puget Sound, we should ensure that the successes and failures from each large survey are well publicized and discussed.

I have asked the authors presenting the papers in this session to share with us the goals, approaches, and techniques used in the intensive surveys they managed. The authors have discussed which tools and measurements included in their studies were useful and which ones they would not recommend be used or attempted in the future, or at least used with caution. These insights will be useful to both project managers hoping to maximize the efficiency of future intensive surveys as well as to the scientists who may be tasked with developing specific components of the major investigations. Individually and collectively, these papers should help laymen and scientists determine the value and efficiency of some of the past intensive/expensive surveys, as well as guide the development of similar surveys in the future.

Environmental Assessments of Puget Sound Performed by NOAA

Edward R. Long

Two major programs have been conducted by NOAA in Puget Sound. A wide variety of studies using many methods were conducted under these two programs. The purpose of this presentation is to review the research that was performed and to discuss the relative merits of the various studies and methods. The first involved documentation of environmental conditions in the Strait of Juan de Fuca and northern Puget Sound preliminary to anticipated transshipment of Alaska crude oil through the area. The second involved an assessment of the occurrence, fate, and effects of potentially toxic contaminants in the central and southern basins of the Sound. The former program was performed in the U.S. waters north of Admiralty Inlet; the latter in the waters south of Admiralty Inlet.

Environmental Assessment of the Strait of Juan de Fuca

Overview

Various proposals were under review in the 1970s to transship North Slope crude oil from Alaska to the lower 48 states. They included overland pipelines through Canada, tankers to California, tankers to Cherry Point, tankers to Clallam County, and tankers to Port Angeles. The options involving tankers to Washington State ports included either under-the-sound or around-the-sound pipelines that eventually would take the crude to refineries in the Midwest. Very little data existed on the basic oceanographic and biologic properties of the Strait of Juan de Fuca which could have been affected by all of the proposed alternatives. Consequently, a joint NOAA/EPA cooperative assessment of the length of the Strait and the San Juan Islands area was initiated.

Baseline concentrations of petroleum, the microbial processes and rates of petroleum degradation, the biological communities at risk to oil spills, the rates of recovery of oiled intertidal communities, the potential patterns of oil spill transport, and the forcing factors (winds, water currents) that would influence the fate of spilled oil were documented in the first program. The work was performed during 1975-1980 and was funded in part, by the U.S. EPA. More than 100 technical reports, and articles were published as a result of the project. The results of the individual studies were summarized by Kopenski and Long (1981).

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Summary of individual studies

Intertidal sediments and mussels were analyzed from 23 sites in the study area and found to be relatively free of petroleum hydrocarbons. Only in Port Angeles Harbor and near the March Point refineries were appreciable concentrations found, and relative to the urban harbors of the central basin which were studied later, the degree of contamination was low.

Water circulation patterns in the Strait of Juan de Fuca are very complex and variable in time and space. However, they generally follow the pattern of most estuaries where less saline surface waters flow toward the Pacific Ocean and more saline bottom oceanic water flows easterly (landward) into and through Admiralty Inlet. Based upon this pattern, surface-borne oil spills would be expected to drift westward to the Pacific. However, research indicated that during certain meteorological conditions, the surface currents can be reversed--eastbound--at the surface for many days at a time. During these events, oil spills in the Strait could conceivably be transported toward, and perhaps, into Puget Sound.

Since Port Angeles was under intensive scrutiny as a port for transshipment of the crude oil from tankers to a pipeline, several special studies of water currents were performed there. These studies showed that nearshore currents were often eastbound between the entrance to the harbor and the tip of Dungeness Spit. In addition, a tidally induced gyre often formed southeast of the Spit. Consequently, a very likely scenario for oil spilled in Port Angeles would involve transport eastward to and beyond Dungeness Spit and entrainment in the water between Protection Island and Dungeness.

Once oil is spilled, numerous factors control its fate. One of them is the ability of micro-organisms to chemically degrade it to less noxious compounds. Research determined that the rate of microbial degradation of spilled oil was controlled by low temperatures and limited nutrient availability in the Strait. Ironically, degradation potential is highest in areas, such as Port Angeles Harbor, that are now chronically polluted. The organic material and sources of nutrients keeps a steady population of micro-organisms at the ready to more quickly attack an oil spill. In many of the sandy beaches that border the Strait, there are very small populations of these micro-organisms and they are slow to react to spilled oil.

Areas of the shoreline with rock, cobble, or mud/gravel mixtures support the highest densities of intertidal biota. But, since rock surfaces usually do not accumulate oil, the most vulnerable habitats are the mud flats. The most productive and extensive mud flats along the Strait are near Dungeness. Very high abundances of intertidal algae, invertebrates, fish, seabirds, and mammals (seals) were found there. Up to 50,000 organisms per square meter were found in some intertidal mud samples there. The shrimp-like animals that are the favorite prey of juvenile salmon were most

dense there. Accordingly, the densities of subtidal fish also were high near Dungeness. The colonies of seabirds at Protection Island were found to be larger there than anywhere else in the area; including over 17,000 pairs of rhinoceros auklets. About 200 harbor seals live in the area around Dungeness and Protection Island. The mud flats and nearby marshes at Dungeness were determined to be the most sensitive to the effects of oil: oil is trapped in the mud and marsh grass rhizomes and is difficult to remove.

Experimental work with oil in intertidal mud, sand, and rock habitats showed that biological recovery following an oil spill would take up to 46 months, 31 months, and from 3 to 13 months, respectively, with no artificial (mechanical) removal of the oil. The intertidal mud/gravel habitat at a commercial clam farm in Discovery Bay was discovered to recover the slowest from the effects of oil.

The relative merits of the studies and uses of the data

The majority of the data from the program were on hand during the final months of hearings, debate, and negotiations concerning the issuance of permits for the Northern Tier Pipeline. The proposed pipeline would have either run from Port Angeles to a point south of Dungeness and under Admiralty Inlet to Whidbey Island and east to Minnesota or run from Port Angeles and around Puget Sound through Olympia and east to Minnesota. The data were used to describe the oceanographic processes that may stress the underwater portion of the pipe, estimate the risk of spills and spill trajectories, identify biological resources at risk, and the possible rates of recovery by biota following a spill. The data from the oceanographic and biological studies were particularly useful in these hearings, and provided powerful arguments against the pipeline construction. Data from studies of microbial degradation of oil, recovery of oiled rock substrates, baseline rates of algal growth, and rates of sedimentation of oil were less useful.

The data from surveys of marine birds helped identify Protection Island as an area of special concern. It was subsequently established as a wildlife refuge to protect the species that nest there.

The oceanographic data, spill trajectory models, rate estimates of microbial degradation of oil, rate estimates of recovery of intertidal biota, baseline petroleum hydrocarbon data, and marine bird data were used in a joint Federal/State response to an oil spill from the ARCO Anchorage in Port ANgeles harbor. These data proved to be the most useful in that response. These data would likely be used in any other subsequent oil spill from tankers or barges in the Sound.

The methods used in the oceanographic studies were also used in similar work in Puget Sound. The chemical analytical methods were expanded and refined for use also in Puget Sound.

The studies of marine mammals were not particularly useful with regard to the oil transshipment issue, but provided the first comprehensive count of populations in the area that were very valuable to resource protection agencies. THe studies of epibenthic zooplankton were performed late in the Program and in a small study. Since these animals are an extremely important link between nearshore detritivorous biota and valuable fish (including salmon) and are sensitive to contaminant effects, it was an oversight to have not performed more intensive surveys of their stocks and productivity.

Puget Sound Marine Ecosystem Analysis

Overview.

In the late 1970s, the data from a few scattered studies of potentially toxic chemicals in the Puget Sound basins were available. However, no comprehensive surveys had been performed to determine the occurrence and concentrations of a broad suite of chemicals. Very few measures of biological effects had been made, and none had been made Soundwide. Only preliminary information on the processes and rates of contaminant transport was available. Yet the sketchy data available suggested that there may be potentially serious problems in at least parts of the Sound. This program was performed during 1976-1985 with funding by NOAA, initially as the MESA (Marine Eco Systems Analysis) Project and, later, as part of the program of the Office of Marine Pollution Assessment.

This program documented the occurrence and concentrations of chemical contaminants in sediments, demersal fish, marine birds, marine mammals, salmon, and microlayers; the occurrence and incidence of histopathological disorders in fish and invertebrates; the degree of toxicity of sediments and microlayers; the potential for exposure of recreational anglers to contaminants in fish; the effects of contaminants on epibenthic and infaunal communities; the history of contamination of sediments; the incidence of histopathological and reproductive disorders in seabirds and marine mammals; the processes and patterns of water and contaminant transport; the temporal trends in environmental conditions; and a proposed monitoring program for Puget Sound.

Summary of individual studies.

Research under this program initially involved the identification of trends in contamination of sediments and bottomfish (mostly, English sole). Surveys in many parts of the Sound showed that histopathological disorders in the fish were most prevalent in the urban harbors and waterways where the sediments were most contaminated. These areas included several of the industrial waterways at Tacoma, the Duwamish Waterway at Seattle, and the Everett Harbor/ Mukilteo area. Later, part of Eagle Harbor was determined to be highly contaminated. The incidences of the most serious of the disorders, neoplasms of the livers, were very low in the central

basin and rural (reference) bays and gradually increased at sites leading into Elliott Bay and into the Duwamish Waterway. The same pattern also occurred at sites in Commencement Bay, where high incidences were found in the industrial waterways. Over a 5-year period, the incidence of some disorders increased at some sites (e.g., off the Seattle waterfront) and decreased at others (e.g., some Tacoma waterways). Data on disorders in clams and crabs were more difficult to interpret, since sample sizes were variable and usually small.

These surveys were followed by studies of the toxicity of sediments at many places. The results also showed highest sediment toxicity in the Tacoma waterways, along the Seattle waterfront, in the Duwamish, in Sinclair Inlet, and in part of Everett Harbor relative to other areas. Over 600 sediment samples have thus far been tested for toxicity. These sediment bioassays were performed with a variety of animals, notably amphipods and oyster larvae.

In all these studies, the rural bays and the central basin of the Sound were found to be less contaminated than the urban harbors and waterways. Subsequent surveys of the toxicity of sea-surface microlayers also confirmed that highest contamination and toxicity usually occurred in samples from parts of Elliott and Commencement bays nearest sources.

The research on bottomfish as an environmental assessment tool led to questions of the safety (human health) aspects of consuming fish from the Sound. Analyses had usually been performed on the livers of the fish, since that organ often accumulates highest chemical levels and therefore its analysis made it easier to detect contaminants. Analyses of the edible muscle of salmon, cod, and English sole showed a big difference in contamination among the species; the salmon being the cleanest. Later, a more comprehensive study of the consumption rates and patterns of urban recreational anglers determined which species were being eaten (mostly salmon and various cod and rockfish species), how they were prepared (usually fried), and how much was being eaten (about 10 grams of fish per angler per day). Finally, the fish were chemically analyzed to determine what contaminants were in the muscle tissue and, using the consumption data and the chemical data, estimates of daily contaminant uptake were made. The data were provided to the appropriate health authorities for possible action.

Very little long-term monitoring of the quality of Puget Sound has been conducted. Nevertheless, a synopsis of available data was prepared to determine if the quality of Puget Sound had been changing with time. A wide variety of indicators was used, ranging from bacteria counts in water to harbor seal abundance. Some of the data were inconclusive and some showed that in parts of the Sound, some indicators suggested environmental quality was decreasing. But, the preponderance of evidence showed the Sound was increasing in quality. A suggested plan for monitoring the Sound was developed and published to help alleviate the problem of lack of a comprehensive monitoring program.

Analogous to the research on disorders in bottomfish, research on the health of seabirds and marine mammals was conducted. Some of these animals had been discovered to be very highly contaminated with persistent organic compounds. However, the biological data did not show any major health or reproductive effects among the birds and mammals.

Over 100 reports, articles, and books have been published by NOAA on various aspects of the environmental quality of the Sound. Many environmental assessment tools now used routinely elsewhere, were initially developed and tested in Puget Sound. It has been an excellent laboratory for determining the degree and effects of contamination.

<u>The relative merits of the studies and uses of the data.</u>

The research performed under this program was successful in identifying areas in Puget Sound in which contaminant levels and incidences of biological effects were high. A survey approach coupling chemical analyses of sediments and demersal fish, histopathological analyses of the fish, and bioassays of the sediments was later adopted in the "Urban Bay Approach" of EPA Region 10 in their studies. This approach (so far, with the exception of the bioassays) is also employed nationwide by NOAA in our National Status and Trends Program.

A concept developed in the Puget Sound studies, the "Sediment Quality Triad," was based upon the observed need for chemistry, toxicity, and benthos data to fully assess sediment quality. It has been subsequently applied in other studies in Puget Sound and in San Francisco Bay, southern California, and the Gulf of Mexico. Sediment bioassay methods initially developed and tested by EPA and NOAA in Puget Sound are being evaluated as candidates for nationwide use in the Status and Trends Program.

Most of the sediment bioassays were performed with amphipods and/or oyster larvae; and these tests have been used extensively in many subsequent surveys. Other tests of sediment quality involving mutagenicity in fish cell cultures, survival among copepods, altered respiration rates in worms, and impaired reproduction in worms, have not been used extensively by others. Also, in situ bioassays that involved examining recruitment of epibenthos on artificial substrates were very successful at identifying differences among sites, but were not followed by other investigators. A bioassay using the Ames test of mutagenicity in bacteria was not performed again by others.

The research on microlayer contamination and toxicity served to document that the air-sea interface, as well as the sediment-water interface, is a place where contaminants can accumulate. Research in Puget Sound has been followed with similar studies off southern California, in Chesapeake Bay, and off Georgia where toxic samples have also been observed.

Chemical analytical methods initially developed in Puget Sound research have been adopted nationwide in other research and monitoring programs. They are now used in NOAA's National Status and Trends Program. Initial documentation of oceanographic and sedimentological processes in the Sound has been followed with additional research and the development of predictive fate models.

A Puget Sound monitoring program initially developed by NOAA served as the basis for programs developed subsequently by EPA and, in turn, by the Puget Sound Water Quality Authority to satisfy their respective needs. The latter plan incorporates many approaches initially developed in NOAA research: The Sediment Quality Triad, fish histopathology, microlayer contamination, marine bird and mammal censuses in ambient receiving waters.

Among the many studies performed in the Sound by NOAA, some the approaches have not been used extensively or at all in subsequent research. Research on contaminant levels and measures of effects in sea birds and mammals, while of great ecologic importance, has unfortunately not been followed with subsequent studies. Surveys of microlayer toxicity showed that neustonic biota were potentially at risk from contamination, but additional work has not been performed. In situ bioassays using recruitment of artificial substrates have not been performed again. Sediment bioassays with Ames-type bacteria, with worms tested for altered respiration rates and with worms tested for altered reproductive success have not been performed again. However, bioassays of sediment extracts to determine mutagenicity in trout cell cultures led to development of other tests of mutagenicity, including those of microlayers.

Summary

Both of these programs demonstrated the need for multi-disciplinary research in environmental assessments. In the assessments of contaminant distributions, the biological data collected synoptically with the chemical data were very important in providing relevance to the data. The documentation of the relative importance of intertidal habitats along the Strait of Juan de Fuca to biota coupled with the estimates of recovery from oil spills clearly identified mud flats as habitats to protect.

Both programs demonstrated the need for central management of the various studies, such that coordination of studies and interpretation of the results are optimal. Requests for information and data tapes from both programs continue to the present time and can be filled most easily from a central management office. Both programs benefited from a certain amount of risk taking and a willingness to test and evaluate innovative ideas that some detractors at the time thought would not work. Though some of these innovative ideas, indeed, did not work, others provided excellent information and have been used extensively by others. The value of having access to many scientists with a variety of opinions to help in formulating research direction and approaches was very apparent. However, even the testing of new innovative ideas was conducted

under the overall programmatic umbrella developed early in the programs. It was very important to have a clear set of technical objectives set *a priori* upon which all the studies were focused. It was important to set attainable objectives within the funding limits that were established.

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Southern Puget Sound Water Quality Study:
The Technical and Management Perspectives

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Introduction

The cities of Lacey, Olympia, and Tumwater, and Thurston County (LOTT) proposed to expand the discharge to Budd Inlet from the LOTT Secondary Wastewater Treatment Plant. Because of the chronic water quality violations within the inlet and other discharge-related issues in the South Sound, the Department of Ecology contracted with URS Corporation to perform the Southern Puget Sound Water Quality Study, an intensive and expensive undertaking. It consisted of three separate studies related to estimating the capacity of the South Sound to accept new or expanded secondary wastewater discharge.

The first was the development of a Discharge Zone Classification System (URS, 1985). This classification system was intended to be used as an early planning tool for identifying areas where existing water quality or beneficial uses would not limit consideration of new or expanded secondary wastewater discharges.

The second effort evaluated the circulation and flushing characteristics of the south Sound area (URS and Evans-Hamilton, 1986). It was designed to compare various flushing estimates and determine the maximum allowable wastewater discharge rate into any of the inlets. This was based on maintaining Ecology's 100:1 dilution ratio (Ecology, 1985).

The third study (URS, 1986) focused on Budd Inlet where fish kills and low dissolved oxygen concentrations occur. Algal blooms in the late summer and early fall and their subsequent decline and decay, had been implicated as the major cause of the oxygen depletion in the inner inlet. The LOTT wastewater discharge in the inner inlet was also known to be the major nutrient point source in the inlet. The primary research questions were: What was the contribution of the wastewater discharge toward algal blooms in the inner inlet? How were the blooms linked to the low dissolved levels? And what, if any, measures may be taken to resolve the problem?

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A computer model was developed to simulate the complex hydrodynamics, transport, and ecosystem dynamics of Budd Inlet. The study included two intensive surveys to be used for model calibration and verification, two detailed point- and non-point source bacterial surveys, a two-dimensional box model study, modeling of the dynamic flushing efficiency at points within the inlet, benthic flux survey, and point source water quality surveys over a one-year time period.

These studies were somewhat discrete, in both the outcome and technical complexity, and each should be discussed individually.

Technical Perspective

Discharge zone classification system

The Discharge Zone Classification (DZC) System was developed to identify areas in Southern Puget Sound where new or expanded secondary wastewater discharges should be avoided to prevent degradation of existing water quality, and to avoid serious impacts to existing beneficial uses. The resulting screening tool is intended to be used by planners in siting future secondary wastewater discharges. By consulting the DZC map early in the planning process, planners can avoid areas where existing poor water quality conditions would be exacerbated and where beneficial uses, such as commercial shellfish beds, would be eliminated. The DZC system also helps NPDES applicants determine whether adequate initial dilution can be achieved at a given site.

It is important to note that the DZC system is intended as a "first-cut" screening tool and is not intended to replace the need to conduct site-specific studies to define specific impacts to water quality, beneficial uses, and other elements of the environment required under SEPA, NEPA, and other regulatory requirements.

The DZC System includes a series of maps that show: (1) areas that are not presently considered suitable for siting future wastewater discharges, and (2) areas where future secondary wastewater discharges would be considered by the Washington Department of Ecology. In developing the maps, areas characterized by frequent water quality violations were identified as "not presently considered suitable." In addition, areas where existing beneficial uses would be significantly harmed or eliminated by a secondary discharge were identified on a series of map overlays. Buffer areas around some beneficial uses such as shellfish beds, were also identified.

The water quality violation map and beneficial uses maps were then integrated to produce the DZC map. Beneficial uses that were considered in developing the map included: commercial shellfish harvest, personal-use shellfish harvest, floating aquaculture, water-contact recreation, fish and wildlife resources, sport fishing, commercial fishing, parks, and dredging projects.

Dilution potential is an important consideration for siting wastewater discharge facilities. It was not possible to develop a map showing areas of Southern Puget Sound where adequate initial dilution would be possible for all prospective projects, because initial dilution depends upon a variety of factors, including diffuser design characteristics and the quality of the effluent. Actual dilution effectiveness must be determined on a case-by-case basis using project-specific information.

The DZC system that was developed does, however, provide dilution guidelines and a sample case of dilution evaluation using the EPA Plume Model (Muellenhoff, et al., 1985) and assumed model input parameters. The resulting map shows areas where 100:1 dilution can be attained for the sample case. This map can be used by planners as a first-cut screening tool, with the recognition that site-specific modeling would still be needed for a prospective outfall site.

Any future efforts to expand or update this concept should consider the following recommendations:

1. Since the Discharge Zone Classification System maps were developed, additional Puget Sound resource mapping has been done in conjunction with the Puget sound Atlas (Evans-Hamilton and D.R. System, 1987). This information base should be consulted by planners involved in siting secondary discharges in Southern Puget Sound.

2. Use of a computerized Geographic Information System would be useful in providing greater precision in locating resources and creating overlays. A database could be developed to provide detailed information concerning the resources at particular locations.

3. Development of Discharge Zone Classification maps for other areas of Puget sound could be useful to planners in considering potential sites for future secondary discharges. Although considerable resource information is available in the Puget Sound Atlas (Evans-Hamilton and D.R. Systems, 1987) and other materials, no integrated system exists for other areas of Puget Sound to assist early planning efforts in locating secondary discharges.

4. Beneficial use criteria used in the study were developed by a relatively small study team. To improve agreement related to evaluation criteria, an advisory group of interested and affected parties should be convened to discuss and identify by consensus the evaluation criteria to be used in developing the Discharge Zone Classification map.

Circulation and flushing characteristics

The first objective of the circulation and flushing analysis was to use the historical data and compare the methods and varying results presented in earlier flushing estimates. Once evaluated, the most defensible method, considering the compiled available data, would be employed to evaluate wastewater discharge capacity in each of the South Sound inlets. Tidal prism and water/salt balance methods were evaluated and the sensitivity of the latter method discussed. Flushing estimates for the net seaward transport were then calculated using current measurements and cross-channel areas. Estimates of refluxing were made and included in the flushing rates for each inlet. The maximum discharge rate model was then developed and applied to each inlet. It was assumed that the dilution ratio under worst-case conditions could not be less than 100:1.

The report did what it was supposed to do, explain the differences in flushing estimates. It also expanded the use of the methods to derive maximum discharge rates for several areas in South Sound. However, it did not refine or develop a better method for calculating flushing. This would have made the report more useful; however, it would have required an effort beyond the scope and budget of the project. Adequate budget must be available for any similar effort in the future.

Budd Inlet Study

The state of our knowledge regarding estuarine systems to date indicates that the dynamic nature of estuaries dominates their character. Our understanding of estuarine systems is only now moving from a historical qualitative viewpoint to a physiological quantitative viewpoint in which there are many simultaneous interactive biogeochemical processes occurring at different rates. These processes are occurring within a dynamic environment where the physical transport processes influence and may sometimes limit the rate and extent of the biological processes.

Given the limited understanding of estuarine processes, it was considered inappropriate to directly apply results gained in studying individual estuaries to Budd Inlet. Therefore, the challenge in the Budd Inlet Study was to identify the major physical and biological processes influencing dissolved oxygen concentrations in the inlet and to design a sampling program that would measure the major parameters involved in the processes. Key considerations involved selecting the type, number, and timing of samples to be collected so that the measurements would cover the important parameters involved in the dynamic interactions, yet not overwhelm the budget. Other considerations involved assumptions regarding the major processes assumed to be influencing the dissolved oxygen concentrations. These had to be well enough understood to be reasonably modeled.

There is also an inherent risk when conducting an applied research study in a dynamic estuarine system that is poorly understood. The risk stems from the fact that reasonable assumptions must be made and testable hypotheses posed before the sampling program is designed. There may not be a way to determine if the assumptions are either complete or correct until after the data have been collected, analyzed, and modeled.

In the case of the Budd Inlet Study, one of the key elements to its success was to have a clear understanding of the project objectives and a solid working hypothesis around which the study could be designed. This helped focus the study toward key processes within the inlet that were assumed to be controlling oxygen concentrations. Even though the initial hypothesis; that the decline and decay of algal blooms was not found to be the probably cause of the oxygen depletion, the focus on testing major assumptions and processes did eventually lead to an understanding of its probable cause.

What was learned from the Budd Inlet Study that would aid us in developing programs for studying similar complex systems in the future?

1. If possible, programs should be designed to test the major assumptions as early as possible and incorporate a certain amount of flexibility for changing scope and direction after testing the initial assumptions.

2. The overall program budget should be developed keeping in mind that the study is research-oriented and should contain some contingency funds for refining assumptions and hypotheses as part of the research process.

3. We learned an important lesson that is often overlooked when attempting to understand a complex dynamic system such as Budd Inlet. That is, measurements must be taken on a time scale that is substantially less than the time scale of the processes you are attempting to observe. The total time period over which samples are collected should also cover the dynamic range of the important processes.

Management Perspective

The overall project described above had a cost of $300,000. About $260,000 went to URS Consultants, and about $40,000 was spent by Ecology for management and performing selected portions of the analysis. It therefore falls into the expensive intensive class of studies. As in all aspects of life, project-related hindsight is always much better. As one could expect, the three products completed as part of the assessment have had varying utility. The Discharge Zone Classification was, and still is a good concept. It served several purposes in 1985 and should be useful for several years. Specifically, the classification:

1. Compiled and presented several published and unpublished pieces of information in a way previously undone.

2. Notified present and potential dischargers about potential use impacts, sub-standard water quality and the poor dilution in the South Sound area.

3. Forced the regulatory agencies to formalize unstated rules/ guidelines.

4. Provided the non-technical audience with a map (essentially, a picture) of the areas which would be acceptable for a secondary wastewater discharge of 1 million gallons per day.

This information provides insight and a tool to potential dischargers. By using the system, they can quickly and cheaply evaluate a potential wastewater discharge location. If proposed in an acceptable area, as defined by the screening tool, they would have a much easier time securing a wastewater discharge permit. If proposed in an unacceptable area, the proponent would likely have to perform very detailed water quality and use analyses to demonstrate the extent of any potential impacts. Additional wastewater treatment could be required in the latter case. The overall result is that local developers, planners, and regulators are more informed. It was a bargain ($45,000) for the benefits received.

Circulation and Flushing in South Puget Sound was the second product in the assessment. About 17 percent ($45,000) of the budget was spent to provide the following:

1. Compile all pertinent data, determine flushing rates and compare and discuss the rates published in the literature.

2. Collect current meter data from three moorings over a three-month period.

3. Develop a maximum wastewater discharge rate model and evaluate the relative differences between embayments.

Of the three completed products, this was the least directly useful. Originally, flushing was envisioned to be included as a component in the Discharge Classification System. It was to be used to set a maximum wastewater discharge rate for any given embayment, once reached, the waterway would be closed to additional discharge; much like the minimum initial dilution guidelines (Ecology, 1985). This indirect method of determining a maximum discharge rate was to be applied because the need and the budget were not apparent for a South Sound-wide assimilative capacity study. Once the evaluation began, the complex nature of flushing and the resolution offered by existing data precluded its direct inclusion in the Classification. The decision was then made to collect additional data. Due to budget constraints, the sub-basin affecting Budd Inlet was targeted. The resulting data were useful to the Budd Inlet work but not really germane to the original Discharge Zone Classification concept.

The final and largest component of the study ($170,000) was performed in Budd Inlet. Evaluation of the potential impacts from a greatly expanded wastewater discharge into a perturbed receiving water was needed. It was very important that the following issues be addressed:

1. Which nutrient was limiting algal production.

2. Identify the relative contributions from each nutrient source.

3. Model the hydrodynamics and water quality in the inlet.

4. Evaluate the mechanism(s) responsible for the chronic low dissolved oxygen concentrations.

5. Evaluate the cause for the poor bacterial quality in Budd Inlet.

6. Evaluate the impact from each of a number of different discharge locations, effluent qualities, and effluent volumes.

All of the above and more was accomplished but much of the work represented new science. Eutrophication in estuarine waters is poorly understood. The models available for the biological response to nutrient loads in fresh waters are virtually nonexistent for the hydrodynamically complex estuaries. Similarly standards or criteria are not available. The result was that a 10 percent increase in phytoplankton production was determined to be acceptable and that future water quality violations would be minimized at that level. The preferred option results in a decrease from the loads discharged today. We are therefore maintaining the antidegradation policy of the Clean Water Act.

Large, expensive, applied projects such as this one have at least two very important functions. The first is to provide the technical information needed to meet the identified objectives. Education, the second function, is perhaps the most important and often the most overlooked. The affected population, managers, elected officials and regulators can all benefit from the information and concepts which are integral to the needed solutions. If people understand why an action is needed, they are more willing to proceed in a constructive manner.

In this project, frequent meetings, and reviews were conducted. Information was shared freely with any interested party and work was tailored to meet the needs and concerns of the affected community when possible.

The process is not easy and is labor intensive. In the case of the Southern Puget Sound Water Quality Assessment, envision a group of four discrete political jurisdictions, all trying to come to agreement on sewer service areas; treatment and construction costs;

funding mechanisms; and all aspects of short and long term management. Our study was routinely blamed for delaying the communities' progress. These charges continued until Ecology's work was completed. After that, they seemed to blame each other. Politically complicated projects always take longer than expected.

Many of the local issues still remain today and it is a guess as to how they will be resolved. The main point is that the expensive intensive worked and was of more benefit than the $300,000 it cost. It worked for the following reasons:

1. Proper project management.

2. Competent consulting firm.

3. Clear understanding of the objectives and the target audience.

4. Substantial outside review and the flexibility to allow for additional public input when needed.

5. Adequate budget.

6. LOTT's consultant (Parametrix) was cooperative and recognized the benefit of resolving issues.

7. An environmentally responsible community with an adequate tax base.

The applied "expensive intensives" do seem just that--expensive. However, when the cost of the resulting construction projects are considered, they are a bargain.

Acknowledgments

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Reconnaissance-Level Surveys of Eight Bays in Puget Sound

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Introduction

From 1983 to 1985, Battelle/Marine Research Laboratory conducted reconnaissance level field and laboratory studies to better characterize toxic contamination problems occurring in selected urban-industrialized bays (Bellingham Bay, Port Gardner - Everett Harbor, Fourmile Rock - Elliott Bay dump site vicinity, Sinclair Inlet) of Puget Sound. It was envisioned that this goal was best achieved by simultaneously determining levels of contamination in selected baseline or 'reference' bays (Samish Bay, Case Inlet, Dabob Bay, Sequim Bay).

Two major tasks comprised this effort. The first was conducted in 1983 and consisted of preliminary or screening surveys to collect and analyze sediment samples from 101 stations distributed in the four urban-industrialized bays (Figure 1), and at 80 stations distributed in the four baseline bays (Figure 2). The second task was undertaken in 1984 and involved detailed surveys and analyses of the same bays, but at a limited number of stations (32 in urban embayments, 16 in baseline bays). The stations to be resampled in 1984 were the "cleanest" of the clean and the "dirtiest" of the dirty as determined by the 1983 sediment chemical analyses, and within restrictions imposed by sediment type.

Survey Results

A summary of the results of the 1984 detailed surveys is given in this paper: a description of each urban and baseline bay in terms of its bathymetry and sediment chemistry, sediment toxicity, numerically dominant benthic infauna, and incidence of fish and shellfish disease, amphipod and oyster larval bioassay is discussed in relation to the physical and chemical properties of associated sediments. The embayments and the stations in each embayment that showed signs of degraded sediment quality are also identified. Finally, the usefulness of both the 'reference bay' and 'reconnaissance survey' concepts are discussed. The complete survey results are available in two volumes from the U.S. Environmental Protection Agency (1986).

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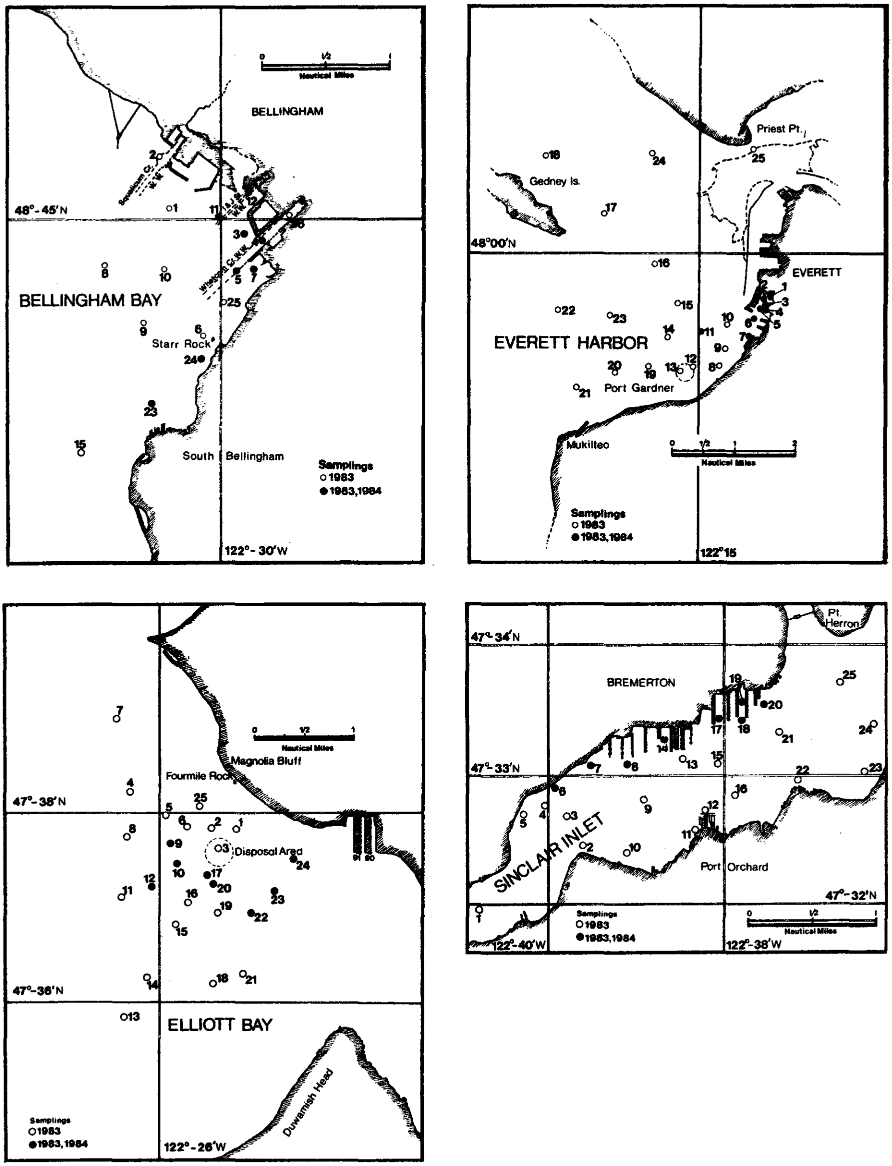

FIGURE 1. Sampling Locations in Urban-Industrialized Bays

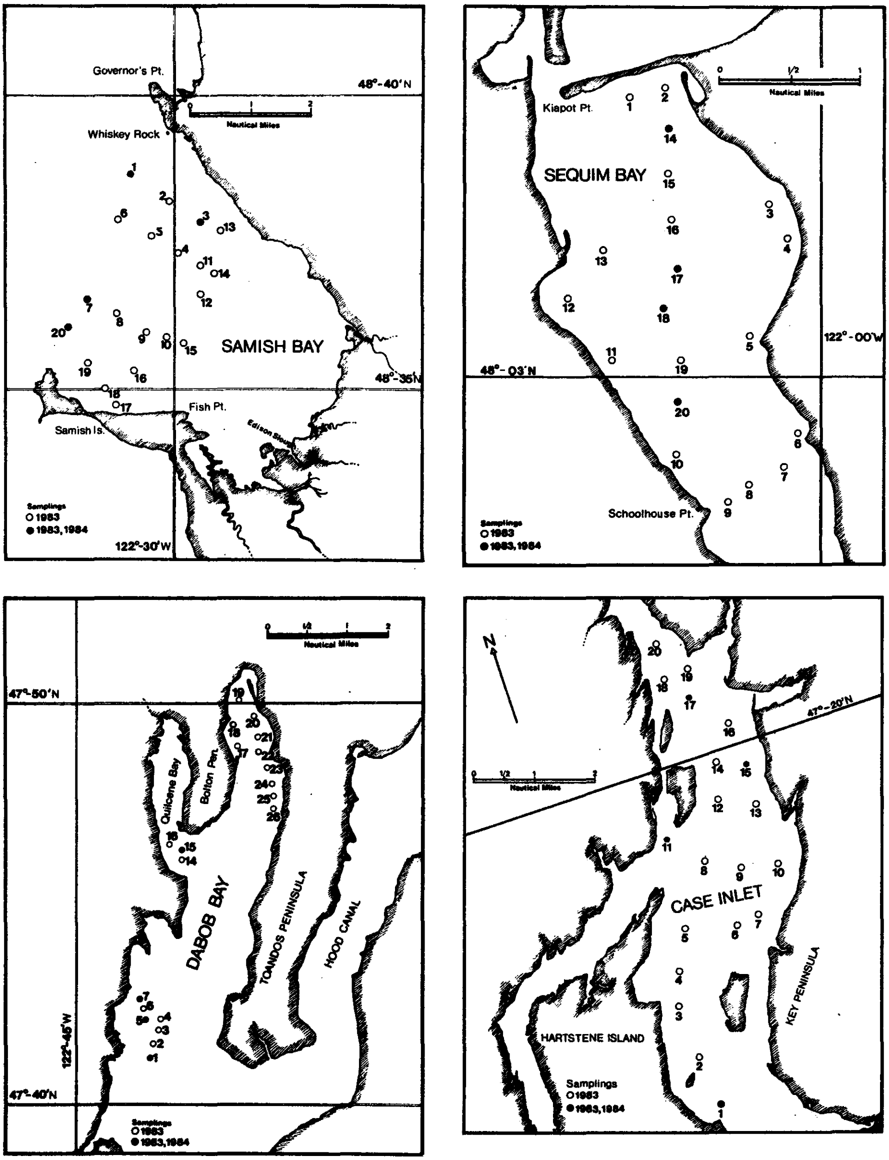

FIGURE 2. Sampling Locations in Baseline (Reference) Bays

Bathymetry and sediment characteristics

The eight bays had different depth and sediment characteristics. Based on the 1984 surveys, the Fourmile Rock - Elliott Bay dump site vicinity and Dabob Bay sampling locations were distinctly deeper (>100 m), contained sediments that were sandier (1.8 to 6.4 phi), and had a lower total organic carbon (TOC) content (0.8 to 3.8%) than the rest. Samish and Bellingham Bays sampling sites were the shallowest (<20 m) and the muddiest (5.4 to 6.9 phi) of the eight bays. Bellingham Bay showed the second highest TOC level (12.1%). Case Inlet, Sinclair Inlet, and Sequim Bay sampling sites were of intermediate depth and exhibited intermediate values for silt and clay (3.0 to 6.5 phi) and TOC (1.3 to 3.2%). Port Gardner - Everett Harbor was distinct from the other bays because it had a significantly higher mean TOC level (7.9%). Here, the sampling sites were also relatively shallow (<20 m) and contained sediments that were intermediate in grain size (3.0 to 5.5 phi).

Contaminant levels

Urban bay sediments, particularly in Sinclair Inlet and at the Fourmile Rock - Elliott Bay dump site vicinity, were found to be contaminated by Ag, As, Cu, Cd, Hg, Pb, and Zn. Other metals (Sb, Be, Cr, Ni, Se, Tl) were found at about the same concentrations in all bays; however, a few urban sediments in Bellingham Bay and Sinclair Inlet were enriched in Sb, Cr, and Ni. Baseline bays generally contained lower metal concentrations, many of which were found at approximately the same concentrations as in pre-1900 sediments (Romberg et al., 1984).

Urban bay sediments, particularly those from Sinclair Inlet and Port Gardner - Everett Harbor, also contained significant quantities of aromatic hydrocarbons and PCB-1254. Other organic compounds occasionally found in urban bays included phthalates and PCB-1260. However, no PCBs were detected in baseline bays and only a few stations in Samish Bay contained detectable quantities of phthalates and aromatic hydrocarbons.

Benthic infauna

A disturbed infaunal community dominated by 'organic enrichment opportunists' was found in all sediment types with high TOC levels (4 to 16%). This shift to enrichment opportunists, primarily nematodes and Capitella capitata, occurred at almost all stations in Port Gardner - Everett Harbor and at several stations in Bellingham Bay. The extent of this shift was less in sandy sediments than in silty sediments.

After omitting the stations with high TOC, the numerically dominant infauna were shown to vary more with sediment type than by bay, except that Case Inlet and Samish Bay had distinctly different infaunas than all other bays. Also, omitting these same stations did not reveal a distinctly different set of numerically dominant infaunal species in urban bays when compared with baseline bays.

Amphipod bioassay

Based on the amphipod survival data alone, the urban bays were not always clearly distinguishable from baseline bays. The Fourmile Rock - Elliott Bay dump site vicinity, representative of urban bay conditions, and Sequim Bay, a baseline bay, demonstrated the highest and second highest mean survivals of 86.5% and 85%, respectively. Similarly, Case Inlet, a baseline bay, and Port Gardner - Everett Harbor, an urban bay, demonstrated the second lowest and lowest mean survivals of 65.0% and 61.5%, respectively.

Correlation analyses indicated significant ($p<0.05$) relationships between the amphipod bioassay and various physical and chemical properties of sediments. Of particular importance were the relationships of amphipod survival to sediment grain size, percent water, organic content (percent volatiles and TOC), and burden of organic compounds (PCB-1254, aromatic hydrocarbons). All such properties were interpreted as accounting for lowered amphipod survival. These analyses also revealed that lowered amphipod survival correlated with increased abundance of organic enrichment infaunal species in Port Gardner - Everett Harbor.

Oyster larval bioassay

Results of the oyster larval bioassays generally paralleled those of amphipod bioassays. The analyses, when taken alone, indicated that urban bays were not always different from baseline bays. Although a majority of stations in Bellingham Bay and Sinclair Inlet, both urban bays, exhibited significantly ($p<0.05$) higher mean percentages of abnormal larvae when compared with controls, the Fourmile Rock - Elliott Bay dump site vicinity, which was also considered representative of urban bay conditions, exhibited no differences when compared with controls. Similarly, although Sequim Bay, Samish Bay, and Case Inlet (all baseline bays) exhibited no differences among mean percentages of abnormal larvae when compared with controls, Dabob Bay (another baseline bay), exhibited higher mean percentages of abnormal larvae at two of four stations.

Correlation analyses showed a significant ($p<0.05$) relationship between percent abnormal oyster larvae and amphipod survival. The trend to higher percentages of abnormal oyster larvae became more evident as amphipod survival decreased.

Fish and shellfish pathology

Flatfish species were not collected in four of the eight bays (Bellingham Bay, Samish Bay, Dabob Bay, Sequim Bay) because of seasonal scarcity. However, these data served to corroborate the results of other approaches used in a summary statistical exercise (chemistry, infaunal analyses, and amphipod and oyster larval bioassays) indicating that urban bays were generally more impacted than baseline bays.

English sole caught in Sinclair Inlet demonstrated the highest incidence of liver, kidney, and gill lesions. Also, two types of

lesions in shellfish were found only in animals from urban bays. Hydropic degeneration/membrane lysis in the hepatopancreas of Dungeness crab and degenerative disorders in the antennal gland of two shrimp species were observed in Bellingham Bay and at the Fourmile Rock - Elliott Bay dump site vicinity. And, although the incidences of serious liver, kidney, and gill lesions in English sole from Case Inlet were low compared to incidences detected in sole from other urban bays (Duwamish Head), these lesions were not detected in sole from Eliza Island (substituted baseline station).

Degraded Sediment Quality

On the basis of a summary statistical exercise that evaluated all data, chemical and biological, urban bays were significantly more impacted than baseline bays. The greatest impacts were found in Port Gardner - Everett Harbor, Sinclair Inlet, and Bellingham Bay. The Fourmile Rock - Elliott Bay dump site vicinity appeared to be the least impacted of the urban-industrialized sampling areas. Not surprisingly, Sequim Bay was the least impacted of all bays. However, Case Inlet and Samish Bay, both baseline bays, showed some indication of degraded sediment quality. All sediments in both bays resulted in lower than control amphipod survival. The amphipod and oyster larval bioassay data from Dabob Bay also suggested some degree of impact.

It was also observed that the most adversely impacted stations in Port Gardner - Everett Harbor were located in the East Waterway. For Sinclair Inlet, they were located in proximity to the Puget Sound Naval Shipyard. In Bellingham Bay, they were associated with the inner harbor.

Clearly, the strength of our survey approach was in the performance of several analyses, both chemical and biological, on the same fresh (unfrozen) sediment sample. The development of a broad based (summary) index of degraded sediment quality also facilitated detection of a wider range of sediment toxicity that would not have been possible if a single analysis or bioassay had been applied.

Relationship of Urban to Baseline (Reference) Bays Concept

It would seem easy to describe baseline or 'reference bay' conditions based on chemical variables. In this study, clear differences occurred in urban versus baseline bays as to concentrations of metals, PCB-1254, and aromatic hydrocarbons. Sequim Bay and Dabob Bay, with relatively low metals and no detectable organic compounds, appear to be excellent choices for reference bays.

On the basis of biological variables, the concept of baseline or 'reference bay' is less clear, and perhaps is better described as representing a continuum of responses consistent with the gradient of contaminants existing between regions of higher and lower contamination in Puget Sound. The results of both the amphipod and oyster larval bioassays best support this interpretation. Although Port Gardner - Everett Harbor, Bellingham Bay, and Sinclair Inlet, all urban bays, exhibited generally lowered

amphipod survival and/or higher oyster larval abnormality, the Fourmile Rock - Elliott Bay dump site vicinity, another urban area, exhibited the highest mean amphipod survival and no difference in the percentage of oyster larval abnormalities when compared with controls. Similarly, Case Inlet, Samish Bay, and Dabob Bay, all baseline bays, showed either a relatively low amphipod survival or a higher than control percentage of abnormal oyster larvae at no less than half of the stations tested. The data could be interpreted as meaning: 1) Port Gardner - Everett Harbor, Bellingham Bay and Sinclair Inlet are all typically urban bays that in Puget Sound are sources of chemical contamination. They occupy one end of the continuum. 2) Sequim Bay is typically a baseline bay located at the opposite end of the continuum, far from urban sources of contamination. 3) Fourmile Rock - Elliott Bay is intermediate on the continuum, located relatively close to an urban source of contamination - Elliott Bay. However, clearly the dump site is unique because not one of the eight stations in the present study indicated degraded sediment quality when evaluated by either the amphipod or oyster larval bioassay. 4) Case Inlet and Samish Bay are also located intermediate on the continuum, but relatively far from urban sources of contamination and closer to Sequim Bay conditions. However, both are close enough to Commencement Bay and Bellingham Bay, respectively, to still show some degraded sediments. 5) Dabob Bay is also located intermediate on the continuum but closest to the Sequim Bay position, that is, relatively far from most urban sources of contamination. The finding of possible degraded sediment quality in Dabob Bay is perhaps attributed to the circulation of contaminants from the main basin of Puget Sound.

In summary, the results of our study support the 'reference bay' concept; however, our results also suggest that the process to select reference bays needs refinement. It is evident that selection should be based on chemical, biological, and physical data. Ideally, a reference bay should contain little or no chemical contamination, demonstrate few or no impacts when evaluated by infaunal analyses and sediment bioassays, but should also possess physical characteristics (depth and grain size) that closely approximate the urban bay(s) to be examined. Our results perhaps suggest that 'reference stations' may be a more appropriate concept than 'reference bays,' particularly when time and funds limit the scope of studies performed in support of regulatory action.

Usefulness of the Reconnaissance Survey Concept

The 1983 screening survey of 181 stations from eight bays was particularly useful in appropriately focusing the 1984 detailed survey. The strategy of selecting the most contaminated stations from the urban bays and the least contaminated stations from the baseline bays permitted limited resources to be directed toward identifying those stations most likely to reveal degraded sediment quality. Moreover, the screening survey data allowed the station selection process for the detailed surveys to be based on data that were recently acquired, rather than on historical data collected in support of other goals. The variability encountered in biological

indices subsequently revealed the wisdom of the selection strategy applied. Another selection strategy would have likely provided less clear-cut biological findings. Consequently, we have learned that sampling strategies must be developed specifically for each study; and if faced with another large sediment survey, we would again recommend that a preliminary or reconnaissance level effort be undertaken to determine which sampling strategy best addresses the study goals with available resources.

Acknowledgements

U.S. Environmental Protection Agency (EPA), Region X, laboratory staff assisted in conducting screening surveys in the fall of 1983, and conducted the detailed surveys in the spring of 1984 themselves. They also analyzed for priority pollutants and performed amphipod bioassays. The National Oceanic and Atmospheric Administration (NOAA) Northwest and Alaska Fisheries Center conducted independent surveys in the same urban-industrialized and baseline embayments to obtain fish and shellfish for analyses of neoplasia and other diseases. Battelle/Marine Research Laboratory (MRL), supported by the EPA under a Related Services Agreement with the U.S. Department of Energy under Contract DE-AC06-76RLO 1830, assisted in conducting the screening surveys, performed metals chemistry for both the screening and detailed surveys, analyzed benthic infauna, and conducted oyster larval bioassays. With the exception of the NOAA neoplasia disease and EPA amphipod studies, MRL also statistically treated and interpreted the data.

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Large Scale Environmental Surveys: The Renton Sewage Treatment Plant Project (Seahurst Baseline Study)

Jack Q. Word[1]
Robert Matsuda[2]

Introduction

The primary objective of the Seahurst Baseline Study was to provide pre-discharge baseline information on a wide variety of environmental parameters. The baseline information would then be used to evaluate the effects of discharging secondary treated sewage effluent on those environmental parameters. It was expected that the effects of that discharge would be small and that highly credible scientific information would need to be available for this comparison. Since little information was available for the for the south central Puget Sound region, a very detailed sampling program was initiated by Municipality of Metropolitan Seattle, (METRO) and performed by the University of Washington. A secondary objective of the program was to evaluate the baseline sampling information to aid in final site designation for the placement of the discharge. The design contractor, URS, Inc., provided appropriate technical staff for siting studies.

Figure 1 shows the study area for East and Colvos Passages that surround Vashon Island and which were centered on Seahurst Park. The study was divided into three general areas of research: (1) water column, (2) environmental health, and (3) sediments. Each of these categories was divided into specific studies (Table 1). Each study area was supported by Chemical Analytical Services directed by Dr. Ahamd Nevissi and by Statistical Design and Analysis services by Dr. Loveday Conquest. Chemical Analytical Services for the organic contaminants were performed by METRO under the direction of Dr. Raleigh Farlow. This information was integrated by a group of senior scientists to maximize research activities; Drs. Quentin Stober and Kenneth Chew of the University of Washington supervised project management with assistance of Jack Q. Word, Drs. Dinnel, Copping and Nevissi.

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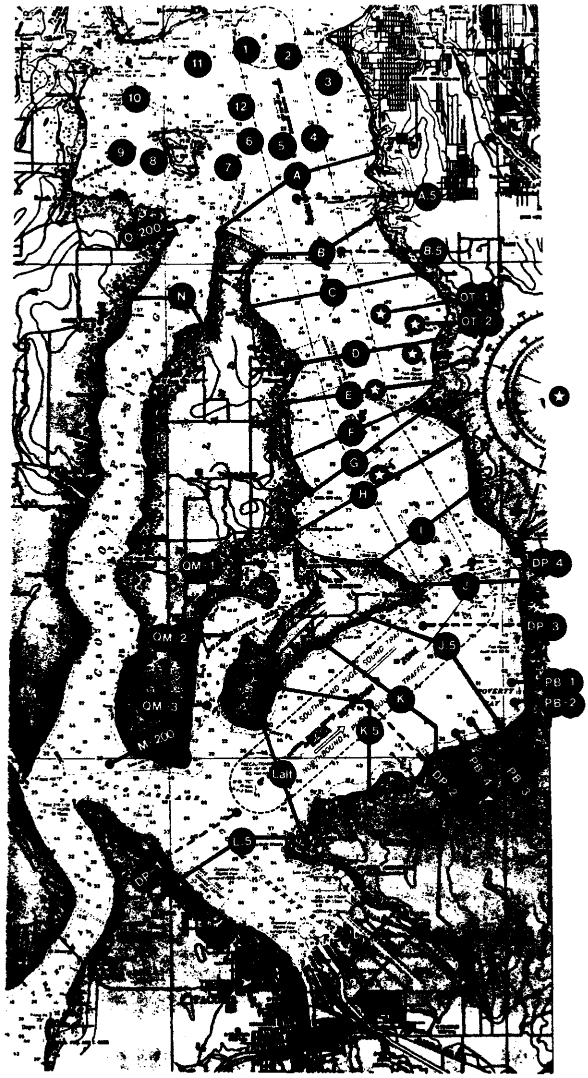

FIGURE 1. Study Areas for East and Colvos Passages for Placement of Renton Sewage Treatment Plant.

TABLE 1. East and Colvos Passage Study Areas.

General Study Areas	Specific Studies	Principal Investigator	Report Reference
Water Column	Physical/Chemical Oceanography	Dr. Curtis Ebbesmeyer	1,2
	Water Column	Dr. James Anderson Dr. Andrea Copping	3,4
Environmental Health Studies		Dr. Richard Kocan	5
	Microbiology	Dr. Jack Matches	6
	Fish Health	Dr. Marsha Landolt	7
	Marine Toxicology	Dr. Paul Dinnel	8
Sediment Studies	Intertidal Ecology	Dr. Ronald Thom	9
	Subtidal Ecology	Jack Q. Word	10,11,12 13
	Fish Ecology	Dr. Bruce Miller	14

Most of the research contained in these programs represented the first rigorous studies of this portion of Puget Sound. Many of the scientific conclusions resulting from these studies have been reported upon in peer reviewed scientific literature. (It is likely that more will be published in the future). Some of the scientific conclusions from these studies include the following:

- Eddy patterns in Seahurst Bay and in other regions of Puget Sound greatly influence the ultimate transport and dilution of wastes discharged in local areas of Puget Sound.

- Contaminants released in Seahurst Bight that travel with bulk water column water tend to travel south where they become a part of the materials transported north through Colvos Passage. This water is then compressed into layers of equivalent density water which are then shuffled like cards into a vertical density stratified water column. Placement of the seawater layer is based upon its density and the receiving water's density.

- Vigorous mixing may recycle water column materials back through Puget Sound. As a result, materials released into one area of the Sound may return to that same area or be cycled into other portions of Puget Sound. Therefore, materials should be managed on a system wide basis.

- The basic seasonal cycles of plankton and nutrients in the photic zone were closely related to the seasonal cycle of sunlight.

- Chlorophyll levels in 1983 were twice the level of any level observed in Puget Sound over the previous 10 years. The presence of El Nino conditions may have had a positive effect on phytoplankton growth.

- Diatom species are the dominant phytoplankton in Puget Sound; they have their maximum growth in the spring. Dinoflagellates were the second most abundant; they were most abundant during the summer.

- Nitrogen was found to be the limiting factor for phytoplankton growth in Puget Sound.

- The abundance and species richness of small infauna in intertidal environments were closely correlated to concentrations of sediment biochemical oxygen demand, volatile solids, organic carbon, sulfide, and percent silt and clay. Maximum abundance of these organisms occurred in spring and summer.

- Secondary effluent increased growth of bladed green alga at concentrations of less than 0.1%.

- A significant fraction of secondary treated sewage effluent particles were less dense than seawater and rose to the surface layer. These particles may act as transport vectors for bacteria, metals, organic contaminants, and probably viruses. Once on the surface they may sink, volatilize to the atmosphere, or be transported by wind. Shoreline impacts of floatable materials from sewage and/or river runoff were apparent in Seahurst bight. Sediments were blackened, anaerobic, had elevated bacterial counts, elevated concentrations of extractable oil and grease materials and had significant fecal coliform and enterococci bacterial counts in shellfish.

- Elevated ammonia levels in Commencement Bay and north of the bay are significantly higher, they control certain phytoplankton blooms and are directly related to a lense of freshwater coming from the Puyallup River.

- The technique of sampling for water column biology while underway proved effective and should be adapted for further studies in Puget Sound.

- There were significant differences in sediment chemistry, benthic infaunal abundance, and species richness which were related to water depth, the east side versus the west side of the Sound and also the north/south direction within Puget Sound. These were predictable and changes in these patterns were directly related to characteristics of erosional versus depositional environments and to nearby sources of contaminant input.

- Benthic infaunal communities could be defined based on dominant taxa structure and the total number of taxa. Appropriate statistical analysis using cluster analysis techniques provided good representations of communities of species within major taxonomic groups. These communities were related to physical and chemical characteristics of the sediments.

- The combination of benthic ecology, sediment chemistry, and current measurements showed that a region of relatively poor circulation existed in the northern portion of Seahurst Bight, resulting in accumulations of higher concentrations of organic material in the sediment and resultant benthic community shifts. These observations suggested that the original proposed location for the outfall pipe was inappropriate.

- Stomach content analysis indicated that fish within Seahurst Bight were found to feed on organisms or on particles which came from domestic sewage. The bacterium, Clostridium perfringes is an excellent indicator of this type of secondary contamination.

- Sediment and tissue contamination could be traced to their sources using relative concentrations of tracer toxicant materials.

- The region of south central Puget Sound was relatively free of fish diseases, and demersal fish communities were most strongly related to water depth and season of the year.

In addition to the scientific observations, important conclusions for planning purposes were also made. These conclusions were the need to account for natural environmental variation and also archival of samples should be collected and retained for future reference.

Natural environmental variation was large in almost all of the types of measurements made during this study. Natural variation was significant, and should be used to aid in directing the selection of the level of biologically significant difference that will be evaluated after man made difference is added. This is contrary to the normal sampling recommendation that there is a given level of statistically significant differences that should be evaluated.

This difference in conceptual design directly relates to the number of replicate samples required in a sampling program. Using the first conceptual design allows sample size calculations to be determined a priori based upon comparison of detectable difference compared to natural variation ratios; the number of replicate samples determined this way is invariate for all measured parameters. The second conceptual design requires knowledge of the degree of variation prior to establishing replicate sample numbers.

The archived samples were often examined or re-evaluated throughout the program. It is expected that these archived chemical, physical and biological samples will undergo continual evaluation to answer questions that could not even be formulated in the past. Since the termination of this program, almost all major studies in Puget Sound have been oversampled and extensive archival of additional materials made. The ultimate use and value of these archived materials cannot be evaluated at the present time, but their ultimate value will surely be great.

Probably the most far-reaching conclusion from this study was recognition of the value of multi-dimensional sampling. The most important conclusions came from combinations of observations made through separate disciplines. An example of these included the identification of physical oceanographic features (gyres) which in Seahurst bight enhanced settlement of organic materials to the sediment, and resulted in altered benthic communities, the source of contaminated bacterial foods to benthic fish. No individual technical discipline would have provided this understanding. Current meter readings indicated relatively rapid speeds with a tendency for an outward flushing of water that would have been the ideal receiving water for the effluent. Fortunately, it was discovered that while the water moved fairly rapidly, it traveled in a counter-clockwise gyre and returned to the original site. Detailed sediment chemistry showed enhanced settlement of organic materials to the sea floor in association with this gyre in the same area of altered benthic communities. Fish were then found to have enhanced levels of bacterial indicators in the stomach contents. These kinds of observations, when compared to regions outside of Seahurst bight showed how unwise it would have been to place another much larger discharge into this bay. This larger discharge would have dramatically effected Seahurst Bay.

The value of specific types of measurements made by the investigators can be determined by asking the investigators or the funding group. METRO responded that given the same set of circumstances, i.e., very little knowledge of the area, relatively clean environment, and public interest in the project, they would not remove anything from the sampling design. The sampling design would have been truncated had there been more information available, and the proposed site of discharge had been in a more polluted environment.

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Duwamish Head Baseline Study:
Post Project Analysis
of a
Baseline Environmental Monitoring Method

Gary S. Mauseth[1]
Andrew C. Kindig[1]
Robert I. Matsuda[2]

Introduction

In 1984 the Municipality of Metropolitan Seattle (METRO) initiated the Duwamish Head Baseline Study (DHBS) to document conditions prior to the operation of the Renton Effluent Transfer System (ETS). The ETS relocated discharge of up to 72 mgd of secondary effluent from the Duwamish River to a depth of 200 m in outer Elliott Bay in Puget Sound, Washington. This study was unique in that three years of preoperational baseline data were collected to address the following objectives:

1. Determine if the effluent plume behaves according to scientific and engineering predictions,

2. Develop baseline studies to establish predischarge "environmental gradients",

3. Inventory pertinent shoreline areas to document present levels of contamination and potential sources of pollution,

4. Collect, analyze, interpret, and archive samples in a way that highlights the data relative to the stated study objectives, and

5. Recommend a postdischarge monitoring plan.

Project Description

The DHBS was faced with the ubiquitous constraint of finite financial resources. METRO and their contractors weighed agency concerns, existing data, and cost, to select parameters for field collection that would maximize baseline information for dollars spent. The baseline study included the collection of physical, chemical and bacterial data from the water column as well as

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physical, chemical and benthic community data from the intertidal and subtidal sediments (METRO, 1986). A paramount concern was to optimize collection of baseline data during a period against which all future discharge impact assessments would be made.

The 1984-1986 baseline data set discussed in this paper consists of sediment biological and chemical parameters from 36 subtidal stations at depths ranging from 50 to 210 m, and ten intertidal stations. The study plan called for subtidal station sampling of five discrete replicate samples collected for infaunal analysis and a single composite sample comprised of subsamples from the top 2 cm of five additional grabs. The result of the latter five grabs was a single datum for each station and period for freon extractables, sediment particle size, trace organics, heavy metals, TOC, Clostridium perfringens and Microtox (TM) bioassay.

Discussion

Initial estimates of variability of many parameters in the DHBS were based on little or no pre-existing long-term, site-specific data and were found to be low. Comparisons over the three years of baseline data collection indicated substantial annual variation for several parameters, most notably freon extractables, particle size distribution, mercury and cadmium. Because resources were not available to support replicate sediment chemistry analyses, it was impossible to determine whether these between year differences were a result of temporal change, a reflection of spatial patchiness compounded by uncertainty inherent in returning to exactly the same station, or a combination of both. Distinguishing between these effects would only be possible with replicate data for each baseline year. Combining all years as temporal replicates of the same preoperational period, as planned, carried an implicit assumption that spatial patchiness was not a significant source of variance and that each individual year's datum adequately reflected the true condition.

Parameters with extreme spatial or temporal variation would not likely serve as useful baseline elements of the long term monitoring program. One goal of the DHBS program was to develop a system capable of providing an early warning of change from the baseline condition (Mauseth, Kindig and Brocco, 1986 and 1987). On a statistical basis, parameters having inherently large variation for any reason would have large minimum detectable differences. Thus, a radical departure from the baseline state would be required before a statistically supported warning of change was triggered.

Based on the biotic infaunal parameters for which annual replicate station data were collected, the overall temporal change for the baseline period was positive. There was an overall decline in "negative" indicator species and an increase in "positive" indicator species. A species index designed to reflect

overall benthic community feeding strategies (Infaunal Trophic Index, Word 1979) supported the conclusion that conditions were improving. Statistical analyses were first run on a two-way basis: looking for positive or negative changes between years in replicate infaunal data. When the focus was narrowed to one-way negative changes between successive years, the number of significant differences dropped considerably, indicating that the general trend between the three years was one of improving environmental conditions. Still fewer significant differences were observed if pre-established threshold minima between years for given parameters were employed in addition to the one-way tests (Mauseth et al., 1986). Cluster analysis of taxonomic composition of five replicate samples per station indicated very similar infaunal community distributions in 1984 and 1985. Infaunal cluster groupings appeared to correlate with depth and grain size. Cluster analysis of 1986 infaunal data presented a marked difference not only from the two previous years, but across isobaths and sediment characteristics as well. Multivariate analysis showed no difference in infaunal data between 1984 and 1985, but showed 1984-85 data to be significantly different from 1986 infaunal data ($P \leq .05$). The results of these multivariate analyses on station replicate data support the argument that temporal variance is contributing more to the overall variance than spatial variance.

Recommendations

Based on the limited DHBS data collected and analyzed to date, we recommend that in designing investigations with similar objectives, study area and budget, the analysis of replicate samples for physical and chemical parameters be given serious consideration. To offset these costs, we offer the following prioritized recommendations for budget reduction:

- Reduce the scope of year two sampling of the three year program,
- Reduce the number of parameters examined, or
- Reduce the number of stations.

In this specific case, we recommend station reduction be the last alternative due to a study design commitment to establish "predischarge environmental gradients" based on the physical conditions of the study site and the predicted behavior of the effluent plume. This program was designed such that if effects were observed, gradients would indicate whether the effluent discharge was the probable cause.

We recommend considering two study elements for review in future investigations, navigation and intertidal sampling. Given the lack of sensitivity of Loran C, a more exact navigation method to increase confidence in returning to subtidal stations to reduce potential sources of spatial error is advised. Eliminating most intertidal chemistry monitoring may also be warranted because of temporal variation imposed by beach dynamics, winds and tides,

so that limited resources could be applied elsewhere in the program.

Study elements we suggest retaining are 1) photographic documentation of sample locations if intertidal sampling is performed, 2) shellfish tissue analysis for contaminants as more representative than ambient water sampling, and 3) the "Red Flag" approach recommended in the long-term monitoring program.

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Summary Statement

John W. Armstrong*

The papers presented in this session have provided a summary of the information gathered and the conclusions reached in several large Puget Sound surveys. In all cases the authors had suggestions about specific tools, methods, measurements or approaches which were: 1) deemed very useful and have since been used by others, 2) deemed to be less worthwhile or of limited use, and 3) deemed promising or useful but which have not received widespread attention or use.

The discussions of these surveys raise issues which are similar for nearly all major surveys and studies conducted in the Sound. The surveys collected several types of information, most techniques/measurements were deemed useful, written reports were produced and the survey was considered to have achieved its goals. But in a broader sense, there are some inefficiencies and shortcomings with most of the Puget Sound surveys conducted to date.

Shortcomings (and potential shortcomings) associated with most major surveys and studies conducted in Puget Sound and elsewhere include:

- o While technically competent project managers and consultants design and conduct most surveys, funding agencies often receive minimal input, guidance and critique from a broader group of scientists and other agency staff as the surveys are being designed,
- o Those individuals who do volunteer to help guide and critique the surveys are often limited by the time they can contribute and by their individual expertise,
- o Interactions among the participants in the surveys are often not encouraged, or may even be regarded as burdensome,
- o Reports from various parts of a survey are often scheduled to be completed at the same time, with individual investigators having limited access to each others "information" in a useful form,
- o Draft survey reports often receive limited technical review, even though they may be sent to numerous reviewers because the reviewers have competing priorities, are volunteers and/or are not technically proficient in certain aspects of the study,
- o The number of final reports printed, and their distribution, is frequently very limited.

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- o Some results don't receive wide-spread distribution, or only receive it if and when they are published in a peer-reviewed journal--a process which may take several months or years, and
- o The general public often receives no concise, understandable summary of the results of the survey or study.

Most of these shortcomings can be overcome if the funding agency makes a conscious effort to ensure that the design and results of the surveys are thoroughly critiqued and circulated. Some suggestions to the funding agencies/project managers for increasing the value, and often the quality, of the intensive/expensive surveys include:

- o Either gain a voluntary commitment from, or consider paying, technically proficient scientists to thoroughly review the proposed survey goals and design, draft reports and conclusions,
- o Encourage and budget for two or three one-day meetings where program design, status (part way through the project--are things working out as planned and are any additional decisions necessary) and finally the draft reports can be discussed and critiqued. Scientists, managers and the public should be invited to attend these meetings.
- o Complete the final reports shortly after the end of the survey and print enough copies to allow a widespread distribution, and
- o Print and distribute two 10-20 page summaries of the results of the survey--one for scientists and one for the public--which critique the approach and provide conclusions.

Some of the agencies which have funded Puget Sound surveys over the past 15-20 years have taken some of the steps described above to increase the value and utility of their work. However, if more agencies made a stronger effort to implement these suggestions, I believe the dollars being committed to Puget Sound and other estuaries would be better spent.

ENVIRONMENTAL DECISION-MAKING

HOW SHOULD WE MAKE DECISIONS FOR MANAGING THE SOUND?

Robert L. Bish,
University of Victoria
Session Chair

INTRODUCTORY STATEMENT

Robert L. Bish*

Environmental decision-making entails the same problems as any significant policy problem: what kind of information is needed, how to obtain the information, how to process policy making and how to implement policy. The three papers here deal with three of these four issues.

Dr. Herbert Curl deals directly with the kinds of information needed to make decisions which balance the benefits and costs in decision-making, and he reargues the importance of the concept of assimilative capacity for benefit-cost comparisons.

Dr's Dave Fluharty and Kai Lee discuss one way to obtain better information: by treating each policy change as an experiment to be monitored and learned from. The process of learning as you go they call adaptive management.

Dr. Tom Leschine and Gary Shigenaka deal with issues of policy implementation - issues that are likely to be of increasing importance as policy administration is decentralized and a greater focus is placed on non-point source pollution control instead of large engineering solutions. The focus on decentralized administration and citizen co-operation is called an implementation perspective.

Together these three papers raise three critical issues for environmental decision-making on Puget Sound.

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Assimilative Capacity
A "Discredited" Idea Whose Time is Yet to Come

Herbert C. Curl, Jr.*

The Problem and Its Roots

Over recorded history, and probably well before, humans have used surface waters and the oceans as convenient waste receptacles. Without articulating it, the consensus was "dilution was the solution to pollution". Unfortunately several phenomena and processes have conspired to make that simple approach totally unacceptable. They were:

- A growing worldwide population.
- An *unrestrained* desire to throw wastes away.
- The development and use of novel chemical compounds whose deliberately engineered properties made them long-lived, toxic, or both.
- Economic systems and a changing ethos that did not penalize waste. (Remember slogans such as "waste not, want not" and "use it up, wear it out, make it do or do without"? If you do, you're at least as old as I am and have a long memory.)
- A change from extensive to intensive agriculture and manufacturing, resulting in concentrated activities based on petrochemical energy and "non-organic" tillage.
- The increasing need to recycle water for drinking purposes in riverine systems.
- The universal human inability, or perhaps unwillingness, to plan ahead compounded by a desire for instant gratification.
- The inability of natural systems to absorb and transform many substances at rates comparable to their input functions.

The Result

I need not bore you with an extensive litany of very familiar results, but I feel compelled to mention a few of them to show their breadth and how incomplete our knowledge is in attempting to develop logical, coherent, systematic approaches to prevention and mitigation, and in order to introduce the question of how much prevention and mitigation is enough. Just a few examples include:

- Litter on all the world's beaches, and in mid ocean, including ghost nets.

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- Anoxia and community changes in the Baltic Sea.
- Nuisance algal bloom in the Adriatic.
- A warming global climate.

Closer to home are:

- Anoxic events in many East and Gulf coast estuaries and coastal zones.
- Some of the highest cancer rates in North America in the New Orleans area.
- Inedible fish in the Great Lakes.
- Increasing incidence of red tides and PSP throughout United States coastal waters.

Still closer to home are:

- Closure of shellfish beds due to fecal coliforms and PSP.
- Warnings on fish consumption in certain areas.
- Diseased fish and possible biological community alteration.
- Habitat loss due to contaminated sediments.

In actuality, our current problems are minor compared to many other parts of the world confronted with major and, in some cases, irremediable alterations. Nonetheless, it is entirely to our credit that we are concerned about the loss of the "pristine" appelation and our loss of (environmental) life style. It will be a long road back for Chesapeake, Delaware and the Hudson-Raritan Bays. We are fortunate in having discovered many of Puget Sound's problems early on. At the present time we are conducting a very elaborate analysis of those problems and their mitigation and prevention.

But:

- Are we asking the right questions?
- Are we using the appropriate approach and appropriate technology in a cost-efficient manner or are we using a bulldozer to dig up a dandelion?
- Are we afraid to conduct *real* benefit-cost analysis because it's not easy and we may not want to know the answer?

Thinking the Unthinkable, or Do I Really Have To Understand the Problem In Order To Solve It?

Just what are Puget Sound's problems, how should we think about them, and what should be done about them? The problems clearly are:

- Closure of shellfish beds, an enormous economic loss, because of fecal coliform ingestion and proximity to sources of coliforms.
- Threats to health, and aesthetic concerns, from combined sewer overflows.
- "Hot spots" from past and present industrial activities with resultant morbidity in demersal fish and general loss of productive habitat.

- Geographic and temporal increases in red tides and paralytic shellfish toxicity.
- Anoxia in enriched, poorly flushed embayments.
- Real and perceived threats from treated sewage effluent.
- Tributary stream flow quality and quantity.
- Potential problems from contaminated dredge spoil disposal.

Problem solving can take two approaches: the administratively convenient one of "total control - one size fits all - all men will wear size forty long and all women size eight" or a more graduated one in which the punishment fits the crime. The latter requires knowledge and understanding and a desire to undertake risk assessment followed by benefit-cost analysis. My assertion is that complicated problems generally require complicated answers. It's not enough to say, "I have a simple, easy, wrong answer to your problem." Fortunately, the First Law of Administrative Convenience runs afoul of several other Laws:

- The Second Law of Thermodynamics-
  All systems are leaky no matter how hard you screw down the lid.
- The Zeroth Law of Economics-
  The harder you screw down the lid the (lot) more it costs you, and
- The First Law of Ecology-
  You can't do just one thing, the corollary of which is,
- The Second Law of Ecology-
  Everything is connected to Everything Else.

These "laws" suggest that there are diminishing returns associated with a totally restrictive approach to pollution abatement. I suggest further that a totally restrictive approach may not even be necessary. Some recognition of this possibility exists. For example, a discussion memo, dated September 3, 1986, for the members of the Puget Sound Council of Governments (1986) suggests a very reasoned approach to waste management. It acknowledged the toxicant concentration levels in the water column were (and still are) far below even the levels of concern for chronic biological effects (METRO 1984) and suggested a reprioritization of concerns if the toxic hot spots were affecting only non-commercial bottom fish and were, in fact becoming cleaner as a result of source control and sediment burial, as pointed out in the 1986 State of the Sound Report (Puget Sound Water Quality Authority 1986).

Thus, as a result of effective source control, although some polluting activities still occur, the Sound appears to be getting cleaner. Therefore, one has to confront the following questions:

- What are the significant problems in Puget Sound in terms of human health, ecosystem health and economic health?
- Are the controls already in place sufficient to deal with these problems?
- Can we (and are we willing to) fine tune those controls as we learn more about source functions and effects?

Instead of immediately replying with the simple, wrong answer that any amount of contamination is too much, I suggest we examine the question, "How much is too much?" and in turn determine the assimilative capacity of the system.

Assimilative Capacity

At a one day conference on Puget Sound pollution called by Governor Gardner, Senator Evans and Congressman Dicks in 1985, a government official remarked that the concept of assimilative capacity had been "discredited" and we should focus on regulation and control leading to zero emissions. My response is and was that the concept had never been tested. The reasons are the same reasons we have many problems in the first place: underfunded regulators, administrative convenience, fear of public decision making, and lack of information. Also, an analysis of assimilative capacity implies benefit/cost analyses which are suspect by all sides because they fear the figures have been juggled. However, I believe it's time we re-examined assimilative capacity as an alternative to zero emissions which can be physically impossible, economically undesirable and ecologically unnecessary.

The assimilative capacity of natural waters has been defined by Goldberg (1981) as, "the amount of a given material that can be contained within it without producing an unacceptable impact on living organisms or non-living resources" (p. 8). This definition is simplistic because Goldberg used the analogy of a chemical endpoint in which the ocean is titrated by a chemical substance until unacceptable damage is noted, at which point the capacity is used up. The situation is more complicated but not so complicated the concept becomes useless.

In actuality, assimilative capacity is a rate of introduction of material at which no unacceptable perturbation occurs, rather than a finite endpoint. In fact, the assimilative capacity for many materials is inexhaustible in time if the rate of input is slow enough. It depends upon the kind of material being disposed of.

Pollutants fall into two general categories: those which are "natural", i.e. elements and compounds which occur normally in the environment but in excess amounts cause undesirable effects. These materials include all of the elements in the periodic chart and many organic compounds. Over evolutionary time biological systems have developed protective mechanisms for degradation or depuration of these materials or have adapted to high levels. Natural "pollutants" sometimes occurring at high levels, include radionuclides in soil, selenium in alkaline deserts, asbestos in rivers, sediments, petroleum hydrocarbons, and nutrients. Biological systems can, of course, be overwhelmed, if the levels are too high or "unnatural". The second category are those which are of human origin and are engineered to be highly toxic, chemically stable or non-biodegradable and, in many cases, all of the above. They may also be, unintentionally, bioaccumulative. This category includes pesticides, herbicides and plastic litter. The assimilative capacity of natural systems for these materials is

limited, if it exists at all, because ecological-biochemical defenses have not evolved to render them harmless. However, other non-biological systems , such as dilution and burial, are also at work, which either reduce the concentration of materials below threshold levels or remove them from the ecosystems.

The mechanisms for assimilative materials in each category are shown in Table I.

Table I. Assimilatory Mechanisms for "Natural" and "Unnatural" Substances

Natural	Unnatural
degradation	burial
decomposition	dilution
depuration	comminution
dilution	
burial	
precipitation	

Goldberg (1981) makes the unfortunate distinction between "pollution studies" which stress protection of public health and assimilative capacity studies which stress ecosystem health. However, many toxic substances are bio-accumulative and affect both human and ecosystem health. To date, and for good reason, human health concerns have been paramount because they are immediate to us. However, ecosystems provide the biological productivity which nourishes and sustains us.

"Acceptable Damage or Perturbation"

The key in the definition of assimilative capacity is "acceptable perturbation". We need to examine what is meant by both words.

Perturbation is clearly the easier word to define of the two, but still not easy. The simplest definition might be:

> "A change for the worse in resource availability, productivity or community structure, which can be demonstrated to be statistically-significantly outside the range of normal variation or secular change, and which can be ascribed to one or more human activities."

One test of this definition occurs when the human activity is stopped and the system reverts to its normal state. Such was clearly the case in the effect of DDT on populations of Bald Eagles, Ospreys, Brown Pelicans and Peregrine Falcons. The removal of untreated sewage effluent from Lake Washington resulted in the cessation of major nuisance blooms. On the other hand, very severely damaged or relict populations and communities already

under stress may not recover when the activity is stopped. This is probably the case with redwood forests and Spotted Owls. There should be no value judgments regarding perturbation, the question is only whether significant change has occurred. Implicit in this definition is the existence of a time series documenting "normal" seasonal and annual variation and decadal secular change. Despite the onus cast on "monitoring" as opposed to "research" there is no substitute for a good time series. A monitoring program following some activity without a preceding time series of key variables is a waste of time and energy. (Should a project be held up because there is no preceding time series? I am compelled to say "yes" and ask that a time series of key variables be begun whenever a permit is requested if one doesn't exist.) Implicit in my definition of perturbation is the concept of a known dose-response relationship between the activity and the effects. The cornerstone of the assimilative capacity concept is the dose-response relationship. If cause-effect relationships cannot be ascertained and quantified we have no way to judge the need or efficacy of a particular action or regulation. Determining cause-effect relationships for "conventional" pollutants is relatively easy, particularly in freshwater. Organic loadings and the resulting changes in pH, turbidity and BOD have been studied and regulated since the early 1900's. Much more difficult to determine have been the relationships between toxicant loadings and biological effects, especially chronic effects.

For the most part, controlled laboratory effects studies have been avoided because of their expense, but they are central to determining exact cause-effect relationships. In most cases a more pragmatic approach has been adopted. For example, Cabelli et al. (1979) attempted to relate incidence of gastroenteritis in swimmers with the prevalence of enteric bacteria at bathing beaches. The two are highly correlated; left unresolved was the point at which one closed beaches based on the incidence of disease because this is a politico-socio-economic decision. In Puget Sound an attempt has been made to relate the results of a suite of bioassays (Microtox, benthic community changes, amphipod bioassay and oyster larvae mortality) to the presence of particular toxicants in the Apparent Effects Threshold (AET) test (Tetratech, Inc. 1986). This test is the basis of the levels established for allowing clean dredged material to be deposited at non-dispersive dredged spoil sites in the Sound. The AET test (as do most other in-situ tests) ignores the synergistic or antagonistic effects of a suite of toxicants.

What do we mean by "acceptable"? This is *clearly* a value judgment, sometimes based on perception, sometimes based on dose-response relationships, sometimes based on the political process, and sometimes based on acute situations impossible to ignore. Acceptability can range from Minimata disease in humans (clearly unacceptable) to fin rot in non-commercial bottom fish (probably acceptable). In democracies the electorate ultimately decides.

The History, Status and Future of Assimilative Capacity

From time to time attempts have been made to evaluate the efficacy and utility of the assimilative capacity concept. One of the first such attempts was the Crystal Mountain Conference in 1979 (Goldberg, 1979). The concept itself was not defined rigorously but it is obvious that many of the participants felt the assimilative capacity for toxic chemicals was being determined quantitatively for many areas. For example, the panel for the Southern California Bight stated confidently (Goldberg, 1979, p. 213),

> "Ocean disposal may continue in the future with minimal adverse effects. Because of increased scientific knowledge of initial dilution, advection, dispersion, chemical conversions and sedimentation, biological uptake and human health, ecological, and aesthetic effects, we now have reasonable ability to predict the effects (and thus the benefits) of changes in discharge practices. However, continued monitoring and research are also necessary to provide a basis for evaluation of disposal systems and modifications as needed."

The panel for Puget Sound (which I chaired), was less sanguine. While endorsing the concept, but not its definition* they stated,

> "We have been purposely vague concerning implementation of the proposed strategy. In order to determine the assimilative capacity of the Sound a large amount of missing data must be obtained... A series of diagnostic models is required in order to describe the physical, chemical and biological functioning of the system as described above..."

They went on to outline a monitoring strategy and made eleven recommendations for determining the assimilative capacity of Puget Sound.

Nearly ten years later, the data base for all variables has increased enormously and models are being developed to describe and predict this behavior of contaminant inputs to the Sound. Ten years later we can also state with some confidence that conditions in the Sound are generally improving through the deliberate institution of source controls and the happenstance changes in source functions. (The exception to this happy situation is non-urban runoff.)

It's ironic to note that Congress was willing to test the concept of assimilative capacity, evidenced by the passage in 1978 of an

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* The panel stated that they viewed assimilative capacity as "not meaningful in terms of some absolute endpoint at which the capacity to absorb pollutants and stress is used up." They proposed, instead, " a continuum of increasing damage and stress in response to pollutant input. The endpoint is socioeconomic." (p. 266).

amendment to the Federal Water Pollution Control Act allowing waivers to the requirement of secondary treatment for municipalities discharging to coastal and estuarine waters (the infamous Sec. 301h.). To obtain a waiver an applicant had to demonstrate that waste discharge would not interfere with the maintenance of "a balanced indigenous population within the receiving waters." That test is actually underway despite the action of the State legislature to make waivers illegal since no major changes in disposal, with the exception of the relocation of the Renton STP effluent from the Duwamish River to the deep main basin, have occurred.

The concept continues to receive attention, however, through the persistence of Goldberg. A SCOPE/ICSU* Workshop (Jong-Cheng Su, 1983) concluded that the concept was "workable" and although the force behind limiting discharges has been focused on human health, their real concern was the protection of ecosystems. Disappointingly, there were few mentions of dose-response relationships, or attempts at quantitation of effects or modeling. In 1984, a National Research Council workshop was convened in Baltimore on Effects of Human Activities on the Coastal Ocean. No report was issued. This is regrettable because the panels dealt with specific issues, one of which was assimilative capacity. The other issues were directly related, including Mussel Watch, the use of mesocosms and effects studies (PRIMA). Apparently no conclusions were reached in regard to assimilative capacity, although the New York Bight anoxia event in 1976, was used as a case study. The summary table for the Workshop tantalizingly stated that "first cut estimates...identified important research to obtain information needed to determine assimilative capacity." Since then it's been pretty quiet on the assimilative capacity front. A review of recent literature shows very few new approaches or refinements, especially quantitative refinement of old approaches. Stop-gap remedies appear to be more cost effective than a thorough analysis of the problem which could lead to greater savings later on. For example the GAO estimated in 1981 that $10 billion in construction costs alone could be saved if most of the 800 coastal treatment plants were to be granted 301h waivers. Savings in operating costs were estimated to be $60 million per year if 260 treatment plants discharging directly to the ocean were granted waivers (GAO 1981). An analysis of the benefits was conducted but analysis of costs (to the ecosystem) was not. Since treatment plants in Puget Sound have no known environmental costs, since the Renton diversion, it would appear that the assimilative capacity of the Sound for treated sewage is virtually untouched.

There have been a few attempts at constructing related cost-benefits models. One by Tamura and Ishida (1985) is an excellent step in the right direction. Using a dynamic input-output economic model they propose a method of total emission control by assigning the elimination rate of pollutants to each production sector.

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* SCOPE (Scientific Committee on Problems of the Environment)
ICSU (International Council of Scientific Unions)

It is readily apparent that the time for using assimilative capacity as a planning and management tool is yet to come. Thus far there has been more hand waving than hard thinking. The missing links are quantitative dose-response curves for pollutants and activities and benefit-cost analysis to determine what point on the curve delimits the acceptable response (and dose) from the unacceptable. Puget Sound might be a good place to undertake such a rigorous analysis.

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NEITHER WILDERNESS NOR FACTORY

Learning from Program Implementation in Natural Resources

David Fluharty* and Kai N. Lee**

Puget Sound is no longer pristine: multiple, sometimes conflicting human uses of this large, complex ecosystem affect its living communities and modify its geography and hydrology. Yet the Sound is so large, so incompletely understood, and so divided among jurisdictions that it is not managed as a coherent whole. Like forests, river basins, and other spatially extended ecosystems, Puget Sound is affected by human activity but the scientific and institutional bases of sensible management remain fragmentary.

What is responsible stewardship in the face of inadequate understanding? We present here the case for adaptive management as the linchpin of an ecosystem regime (see also Hilborn 1987).

Adaptive management is a policy framework that treats program implementation as a set of experiments. Actions taken to protect or manage natural resources provide information about the response of the natural system to human intervention. That information is available whether or not the actions achieve their intended results. But the value of the information can be greatly enhanced by planning to learn through paying attention to possible surprises, statistical power, controls, and monitoring.

Adaptive management, in sum, is deliberately setting out to learn from experience.

We summarize recent experience with adaptive management and examine its possible utilization in managing water quality in Puget Sound.

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The Adaptive Approach

A decade ago C.S. Holling (1978) and coworkers articulated a method they called "adaptive environmental assessment and management" (AEAM). AEAM organizes information from environmental assessment studies so as to enhance understanding of the biological populations affected by environmental change (see also National Research Council 1986, Orians 1986). The adaptive method uses simple simulation models and databases to summarize the emerging picture of the ecosystem or population of interest (Walters 1986). Techniques based on AEAM have been used to a limited extent in managing fisheries in Canada (see, e.g., Department of Fisheries and Oceans 1987).

The use of an adaptive approach to design natural resource programs at the ecosystem level is implicit in the concept. The most ambitious attempt to institute adaptive management at this scale is the Columbia River Basin Fish and Wildlife Program of the Northwest Power Planning Council (1987). Adopted by the Council in 1984, adaptive management provides a conceptual framework to protect and enhance salmon (*Oncorhynchus* spp.) and steelhead (*Salmo gairdneri*) populations of the Columbia drainage which have been adversely affected by the development and operation of hydroelectric power facilities (Lee and Lawrence 1986). These populations, "including related spawning grounds and habitat," have been declared by Congress to be "of significant importance to the social and economic well-being or the Pacific Northwest and the Nation." (16 U.S.C. 839[6]) The Planning Council has taken the statutory injunction to treat the Columbia and its tributaries "as a system" (16 U.S.C. 839b [h] [1] [A]) by recognizing the freshwater and marine ecosystems in which anadromous fish live; the program does not attempt comprehensive planning or management of those habitats, however.

Since the adoption by the Planning Council of an adaptive framework, there have been at least two additional uses of the concept in Washington state. The Timber/Fish/Wildlife (TFW) agreement (1987), a collaborative framework for timber management involving state agencies, Indian tribes, timber companies, and environmental groups, relies on an adaptive approach so that the emerging experience with cooperative resource management can be used to improve its effectiveness over time (Marcy Golde, priv. communic. 1987). Finally, the resource planning section of the King County Planning Department is using the principles of experimental design in developing monitoring procedures for land-use controls and wetlands management (King County 1987a, 1987b, 1987c).

As this recent history suggests, adaptive management has been chosen within political processes, for reasons that go beyond the technical merits. In the governmental context adaptive management is useful because it allows contending interests to work together in a comprehensive policy framework <u>without</u> resolving their conflicts. After two decades of environmental dispute it has become clear that environmentalists are not a passing political fad -- and that industrial society is not a passing phenomenon either. The call for a larger spatial and temporal framework, for more planning and coordination, reflects a search for flexibility within existing institutions, in a setting where the fiscal and organizational abilities or government to expand are at best uncertain.

Adaptive management acknowledges the biological uncertainties facing comprehensive planning while continuing to insist upon the need for a vision that encompasses life cycles and whole habitats. Adaptive management 1) allows large-scale actions to proceed in the face of uncertainty and potential opposition; 2) facilitates communication among management agencies and groups concerned about the exploitation and conservation of living resources (e.g., Hilborn and Luedke 1988); 3) encourages suspension of conflicts, as traditional adversaries jointly develop ways to learn from experience; 4) focuses action on questions of significant uncertainty, in order to lower long-term costs while raising the probability of biological success; and 5) organizes the collection, validation, and use of information for ecosystem-scale planning. Adaptive management, in sum, can transform political conflict over environmental issues on terms acceptable to both environmentalists and the business community.

Such an approach requires difficult changes in the way resource management takes place, however.

- The possibility of failure must be specifically acknowledged and planned for.

- Front-end costs for planning, experimental design, and baseline measurement must be incurred, together with a long-term commitment to continue these activities.

- Interventions must be large and yet not applied universally, a characteristic that makes their justification more difficult.

- And, over time scales long compared to terms of office or duration of agency assignments,

information must be collected, analyzed, and reflected in program redesign.

None of this is readily achieved, especially in institutional structures where implementation is spread out among more than a dozen federal and state agencies, Indian tribes, and intergovernmental and international fora (Wilkinson and Conner 1983). Above all, the institutional fabric must be stable, willing to run and make use of long-term experiments, strong enough to lead and flexible enough to learn. Parallels with Puget Sound are evident.

Implications for Puget Sound Management

Resource management in Puget Sound has followed traditional lines. Water quality, for example, has been managed by single-purpose agencies, largely as a by-product of meeting the sanitation requirements of urbanizing areas.
Traditional coalition-building is widely acceptable and deeply rooted in the politics of water quality, where pollution-control investments have been financed by Congress. Such distributive or pork-barrel policies naturally produce conflict minimization because their primary requirement is to assemble coalitions able to pass legislation. That is, support is sought from representatives whose constituency interests need agree on no more than the expenditure in question; pursuing any more detailed agreement is neither necessary nor, often, constructive. In many cases, there is no other justification for the action taken than that a sufficient majority is achieved.

Rising costs, economies of scale, and, more recently, awareness of environmental quality and concern about toxic substances among the electorate, led to the creation of the Puget Sound Water Quality Authority (PSWQA) -- a planning and coordination body notwithstanding its commanding title. The Authority's approach relies heavily on consensus forged by staff and advisory committees and voted upon by the appointed officials. The Authority is an institutional forum in which interested parties can negotiate consensual plans, without all the formal and informal constraints of fragmented jurisdictions, incompatible single-purpose missions, and established rivalries. The near-term success of this strategy is reflected in an ambitious plan (PSWQA 1986) and wide public and elite support for its funding from state, federal, and private sources.

As water quality programs evolve beyond point sources, however, consensus planning is no more than a starting point, since the implementation of plans will

necessarily involve conflict. Indeed, the consensus behind the Authority plan is incomplete: for example, industry resisted permit fee proposals in the legislation. Consensus planning is vulnerable to becoming a search for the least common denominator -- those policies and programs which are inoffensive, whether or not they are effective or important to managing the ecosystem of interest.

Adaptive management assumes a politically sustainable commitment to a system perspective on management and learning. We do not comment in this paper on whether such a commitment can be built in the Puget Sound. Our purpose instead is to use the adaptive approach as a diagnostic tool, to examine what could be learned if an ecosystem perspective were adopted.

Comparisons and Control A system point of view, for instance, would structure the selection of watersheds to be managed to control nonpoint pollution. Instead of relying on local governments and private actors to volunteer demonstration programs as in the Early Action Watersheds (PSWQA 1986), an experimental approach would outline what could be learned about the biological effectiveness of nonpoint controls by comparing the experience of matched watersheds.

Comparisons can be carried out on different dimensions, ranging from hydrological and biological features to patterns of land ownership and use. But an adaptive perspective would suggest that demonstration programs be coordinated and underlain by a monitoring or detection scheme able to tell the difference between programs that work and those that do not. This is a sharper, hence more valuable question than studying whether a given intervention does any good at all. The Department of Ecology's shellfish protection strategy (WDOE 1984) has been unable to ask that more important question due to lack of resources.

Power of test A recurrent theme of adaptive management is "power of test," the notion that large interventions into natural systems are more likely than small ones to produce unambiguous information. Often, of course, large-scale modifications of the environment raise fears of irreversible damage. Yet when those modifications cannot be halted, it is important still to learn from their unwelcome experience.

It is disappointing, in this light, that the U.S. Navy's planned dredging of the port of Everett to build a base for a carrier task group has not been instrumented for experimental purposes. The dredging operation, which is specifically exempted from the regulations developed by

the Puget Sound Dredge Disposal Analysis (PSDDA), is an order of magnitude larger than the annual dredge spoil disposal operations contemplated in the Sound. Regulatory monitoring is a negotiated part of the Navy program and PSDDA but neither is specifically designed to use dredging policies experimentally to probe for information that could be used in future management (Frank Urabeck, pers. com.). In this regard, the lead agencies in these disposal programs lack the resources, the institutional manadate and a perception of the long term value of the adaptive management approach. There is a significant opportunity cost in not using an adaptive management approach to learn from large scale dredge disposal.

<u>Research, monitoring, and management</u> Research ordinarily takes place separately from resource management. An adaptive approach emphasizes that resource management itself is the most important source of experiments on the natural system. An adaptive approach would accordingly take an experimental approach to resource management in Puget Sound, using management choices to perturb the natural system to develop useful information. Such an effort could help to identify effective and economical policies for protecting and cleaning up the Sound, sooner and less expensively than research that does not use the powerful probes provided by current practices and pending management decisions.

The monitoring plan developed by an interagency advisory committee and PSWQA staff is a consensus document. If funded, the monitoring program would supplant existing efforts -- many of which are conceded to be inadequate or inappropriately targeted -- and build a monitoring regime more capable of measuring resource characteristics of interest to managers. Yet neither the monitoring plan nor the PSWQA plan specifies water quality objectives which management should attain.

Moreover, the monitoring and research plans drafted by Authority-convened advisory committees and staff take insufficient account of how management decisions might provide information useful in learning about the behavior of the Sound and its living communities. As a consequence, the proposals for research and monitoring lack a clear understanding of how natural, residential, and industrial factors affect water quality in the Sound taken as a whole. That is, there is no conceptual foundation for knowing <u>if</u> Puget Sound needs to be cleaner nor how to make it so. The point of an adaptive ecosystem approach is to build such a conceptual foundation over time.

It is important to emphasize that these criticisms are not directed at the Authority, but rather at the social

mechanisms that in the aggregate are responsible for the welfare of Puget Sound. The Authority's charter is to identify solutions. An adaptive perspective puts weight as well on developing a better appreciation of the problems to be solved and rigorously testing the proposed solutions. PSWQA provides the institutional structure for breaking with the traditional management approaches and attempting the bold policy approach of adaptive management. However, the 1991 sunset provision in the Authority's legislation effectively thwarts the long-term approach required for adaptive management.

In the presence of uncertainty and limited resources, solutions to the wrong problems are to be feared as much as inaction; the history of public policy since 1930 is filled with solutions ill-matched to problems. Yet our understanding of the problems to be solved inevitably changes as the solutions are carried out. That is why learning is central and why adaptive management is a valuable tool for natural resource management.

Conclusion

We close with an image of the Columbia River, an image we apply by analogy to Puget Sound. Mankind has built two Columbia River civilizations. We are trying now to invent a third one -- one in which adaptive management has a central role to play.

The first Columbia River was a wilderness. At equilibrium this ecosystem supported a population of perhaps 50,000 people, who built a world centered on salmon (Schalk 1987). This original Columbia civilization lasted from time immemorial until about 1800.

The second Columbia River is a factory. This river is a powerplant; a municipal and industrial water supply that supports 5 million people, 100 times its aboriginal carrying capacity; a plantation of more than half a million acres, fed by one of the largest irrigation works on the planet. The river does these things while avoiding its once-uncivilized floods, and providing an inland waterway for navigation, recreation, and harvest of fish and wildlife. The industrial Columbia is an economic marvel, a river, as the historian Donald Worster recently put it (1985), that died and was reborn as money. For the governing logic of multiple use has been economic return. It is economic value that prioritizes the river's uses and economic growth that sets the tempo of its changes.

The Columbia has not died entirely, nor, significantly, has it been fully reborn. That is why there may be a third Columbia, one whose governing principles are only

dimly seen; only confusingly described. We call it, awkwardly, "equitable multiple use." This is the Columbia River where Indian tribes have since 1969 reasserted their rights to harvest fish, where $100 million of economic value is annually invested in fish and wildlife mitigation -- a sum far out of proportion to the dollar value of the harvestable species that remain.

This third Columbia is neither wilderness nor factory. The world the Indians knew is gone: the wilderness was an integral fabric, a stable tapestry whose natural time scale was the generations; that cloth has been cut. Thus, management by preservation, permitting nature to set the terms on which its constituent species will equilibrate, is no longer possible.

Yet we are also unwilling to follow the logic of the factory to its endpoint, to increase power production to the extent its revenues outbid competeing uses such as irrigation. That means that management which seeks to optimize a single measure of worth will not work either.

So if there is to be a third Columbia River, it must be a place managed by rules and processes that approach the complexity of the ecological interaction itself. That clearly challenges the capacity of human governance -- which is why, as a practical matter, goals set by humans must be provisional, must be revised in light of experience. For the simple fact is that we do not understand our own place within this ecosystem. Yet we are unwilling to relinquish our niche as top omnivore. So the search for objectives has become an intrinsic part of management.

This third, emerging Columbia requires, long-term governance that can address competing objectives in a way that sustains a productive balance among them. This will take new knowledge, a commitment to working hard with one's adversaries, and the ability to learn from biological and social experience.

The need to fashion equitably balanced multiple purposes is as urgent in the Puget Sound as in the Columbia basin. The challenges of doing so are as new as the chemist's ability to detect toxins in the water column, as old as the human community. That combination of the technologically unfamiliar and the politically durable is what makes the promise of adaptive management of significant value.

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Evaluating the Effectiveness of Proposed Nonpoint Source Pollution Control Initiatives

by

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and
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I. The Challenge of Controlling Nonpoint Source Pollution

Unlike the point source pollution at which much existing pollution control regulation is aimed, nonpoint source pollution does not have its origins in readily identifiable and discrete sources. Nonpoint source pollution is typically defined in terms of what it is *not*; in the Puget Sound Water Quality Authority's (PSWQA) 1987 Management Plan, for example, it is described as "pollution that is not discharged through pipes" (PSWQA, 1987). Nonpoint source pollution is generally perceived as a problem whose solutions do not lie in the relatively expensive and technologically complex processes which have generally been used to address point source pollution problems. By and large, it is not the pollution addressed by Congress in the environmental legislation of the 1970s (Shigenaka, 1987).

Because nonpoint source pollution is so different from the problems to which regulatory efforts have traditionally been addressed, its control seemingly demands the application of new and often untested regulatory approaches. The needs for flexibility, site- and source-specificity, and often, local program development and implementation, are frequently stressed in discussions of nonpoint source pollution control (see, for example, Thomas, 1985). The goals of nonpoint source pollution control efforts, like those aimed at point sources, are typically framed as ambient water quality goals or as goals for such biological indicators as levels of shellfish contamination. Yet, the control strategies proposed often represent radical departures from the water quality manager's tradition of centralized "command and control" decision making (Thomas, 1985).

Nonpoint source control efforts in newly emergent estuarine management programs, such as those in the Chesapeake Bay and Puget Sound regions, are now providing a testing ground for a number of alternative water quality management approaches. The rural nonpoint source pollution program recommended by the PSWQA, for example, would vest the authority to design and implement watershed action plans with *ad hoc* local watershed management committees, and would target control efforts on large and diverse segments of local populations heretofore not

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directly subject to pollution control measures (*e.g*., homeowners in unsewered areas, and hobby and commercial farmers). The very concept of a "source control program" would be redefined in a way that includes educational programs and technical and financial assistance as primary elements. In many instances the programs developed might rely on voluntary participation, thereby abandoning the traditional approach of rulemaking, compliance monitoring and enforcement (State of Washington, 1988).

The problem presented by this shift in emphasis in pollution control strategies is clear. While the test of control program efficacy continues to be the ability to improve or maintain environmental quality, such proven technology-based implements as centralized collection and treatment plants appear to be of little relevance to remedying nonpoint problems. Where the primary focus was formerly on discrete, readily identifiable point sources, now the pollution sources of concern are numerous, diffuse and perhaps physically removed from the environmental problems they cause. And, because existing institutional arrangements for pollution control have evolved to operate best through centralized modes of control, the locus of concern in planning and management agencies may be many bureaucratic steps removed from the locus of pollution-generating activity in rural and semi-rural populations. In short, the problem for decision makers at all levels of government in coming to grips with nonpoint source pollution is a classic problem of *implementation*: program success will depend as much, if not more, on the actions of program administrators and their overseers, and on the cooperation of the thousands of individuals whose behavior must change if pollutant loading is to be reduced, as it will on the technical efficacy of the available control systems.

In this article, we use elements of implementation theory to examine the question of how best to design nonpoint source pollution control programs. This perspective highlights the need to address in program development simultaneously two related but different types of questions: 1) What measures are capable of reducing pollutant loading when broadly applied in a particular geographic area of concern, and 2) what implementation approaches are capable of achieving sufficient levels of acceptance and utilization in the target population to assure attainment of program goals? Efforts to develop an "early action" nonpoint control program in the Burley Lagoon-Minter Bay watershed of south Puget Sound illustrate the difficulties decision makers can have in balancing the ability of proposed management options to achieve water quality and biological objectives against their effects on the willingness and ability of the intended target groups to adopt the necessary control measures.

Focusing on potential implementation difficulties in program development leads to an emphasis on seeking and scrutinizing multiple perspectives on nonpoint pollution control problems. The perspectives of top-level decision makers, the intermediaries who would dispense policies, and the recipients of control measures are scrutinized carefully in implementation studies. An analysis of the problem of controlling pollutants associated with agricultural practices suggests that programs which blend regulatory, incentive-based, and public education elements may be necessary, given uncertainties about the effectiveness of particular control measures in achieving water quality goals (important to top-level decision makers) and about how proposed programs will be received by the target population (important to local agents).

Given the nature of nonpoint source pollution, state guidelines cannot be expected, nor would it be desirable for them, to address situations in every watershed. The rationale for delegating much of the "hands on" work for program development to local watershed management committees is clear. Yet, this institutional arrangement places much of the burden on local committees, which must temper the mandate for

environmental effectiveness against the reactions of the local constituents most intimately affected.

In the absence of financial or other incentives, the draft PSWQA guidelines will likely lead to local action programs which emphasize voluntary and educational elements. Recent experience in Puget Sound suggests however that such programs are not likely to achieve dramatic improvements in water quality. Strengths of program measures must be balanced against weaknesses, just as program effectiveness must be balanced against target population acceptance. It is therefore incumbent upon managers at the state level to realize that the most direct means of correcting nonpoint source problems may not necessarily represent the likeliest to be successfully implemented; conversely, watershed management committee members cannot ignore the requirement for effectiveness in submitting a program to the state and to local constituents.

II. Nonpoint Source Pollution Control as a Problem in Implementation

In the nonpoint source pollution control arena, more than in other areas of pollution control, it appears that the success or failure of policies depends heavily on how they are delivered to and received by those individuals whose actions they are intended to affect. Problems of this type focus the attention of public policy analysts on the process of policy implementation, that is, the effort to put an organizational decision into place (Williams, 1975). Implementation, described by Hargrove (1975) as the "missing link" in policymaking, has been defined as "the ability to achieve the predicted consequences in a policy after the initial conditions have been met; the ability to forge subsequent links in the causal chain so as to obtain the desired results" (Pressman and Wildavsky, 1984). As Edwards (1980) has observed, "even a brilliant policy poorly implemented may fail to achieve the goals of its designers".

Because implementation analysis focuses attention on the "delivery end" of the policy making process, it invites different modes of analysis than those which have come to be associated with "top-down" decision making. Top-down decision making begins

> . . . at the top of the [implementation] process, with as clear a statement as possible of the policymaker's intent, and proceeds through a sequence of increasingly more specific steps to define what is expected of implementers at each level. At the bottom of the process, one states, again with as much precision as possible, what a satisfactory outcome would be, *measured in terms of the original statement of intent* [emphasis added] (Elmore, 1982).

The difficulties with this approach to policymaking stem from its underlying but often unarticulated assumptions -- that policies result from the actions of single, well-defined decision makers, and that policies are best represented as the sum totals of their performance against the preselected criteria which define the policymaker's original intent (Majone, 1976). In effect, policy implementation is viewed as a single cause-effect chain flowing from top-level decision makers to the target population, through whatever intermediary agents are necessary. It is driven by the requirement that the selected policy implements address directly and effectively the problem of correcting the ills identified and characterized by the decision criteria.

The problem with the top-down approach is that, because the search for possible implementation problems is not on a par with the analyst's search for corrective actions, unforeseen implementation difficulties may render the goals of policy unreachable.

Because the possibility of discretionary action on the part of policy intermediaries and members of the target population can never be completely eliminated, unintended consequences may serve to subvert the original policy goals. In studies of U.S. Economic Development Administration (EDA) efforts to reduce unemployment in Oakland, California, for example, Pressman and Wildavsky (1984) found that subsidies offered to employers to create jobs for minorities led to few actual employment opportunities for the intended recipients. According to the authors, this occurred because the EDA paid grants to employers before the jobs were filled, rather than subsidizing wages after candidates were employed. In this case, the unintended consequence of awarding grants prior to realization of the intended policy goal, *i.e.*, hiring of minorities, was a substantial reduction in motivation to follow through on the part of the employers receiving the subsidies.

III. A Framework for Examining Implementation Questions in Policy Evaluations

Elmore (1982) describes an analytical framework intended to make explicit those considerations likely to be of primary importance to the population at which policy is directed, and to those governmental agents actually responsible for "dispensing" policy. The idea is to design policy "from the ground up." As a result, the emphasis in identifying goals for evaluating prospective policies is on the target behaviors at the lowest level of the system, where "administrative actions intersect private choices", rather than on the overall health or response of the system of concern. Conditions and actions necessary to realize these goals are then specified at each successively higher level of the hierarchy which leads to top-level decision makers.

An essential feature of this approach is "perspective-taking" ability. The problem to be solved is viewed simultaneously from the perspective of the target population, policy-dispensing intermediaries, and program managers. The selection of appropriate policy approaches is then framed by the answers to such questions as:

- What choices at the lowest level of the implementation hierarchy have the most immediate effect on the problem to be addressed?
- Given these choices, what outcomes would be expected to follow?
- What must implementing agencies do to promote desired outcomes and minimize deleterious effects on their own internal operations?
- What external conditions could affect these outcomes?
- Given all these considerations, what measures are available to the policymaker to effect the desired result? (Shigenaka, 1987)

Such an analytical perspective encourages the examination of prospective policies at the level where they would be administered, focusing on the interface between the "street level" implementor and the program's consumers. Ideally, policy is tailored to accommodate the morass of technical, political and organizational factors which ultimately determine its success, rather than built on the presumption that the effect of such influences can be controlled to its advantage.

The upshot of such an approach is that multiple perspectives -- particularly the perspectives of those at the interface between policy consumers and policy dispensers -- must be sought and utilized in policy development. The importance of such

considerations in implementing nonpoint source pollution control programs is well-illustrated by Novotny and Chesters (1981):

> In translating verbal objectives (*e.g.*, water quality suitable for recreation) into design criteria, the planner or the regulatory agency must choose with care and discrimination the objectives that will be maximized and those that will be treated as constraints. For example, a farmer would treat profits from his production of agricultural products as an objective and maintenance of water quality as a constraint. A planning agency would, on the other hand, consider water quality as the primary objective and maintenance of a viable farming economy as a constraint.

In the following section, we illustrate how such considerations might apply to the control of nonpoint source pollution associated with agricultural practices in the Puget Sound region.

IV. Choices Among Agricultural Runoff Control Measures for Puget Sound

The PSWQA's proposed nonpoint source pollution management regulations (WAC Chapter 400-12) emphasize local development and implementation of watershed action plans. However, fears have persisted in the region's agricultural community that local agents will simply opt for the regulatory programs thought to be preferred by higher level authorities (Doran, 1987). The proposed regulations emphasize that action plans may contain a variety of elements, including

> . . . use of best management practices . . . ; inventories of individual farm plans; voluntary action for prevention and correction; special considerations for noncommercial farms; education; incentives; compliance; and other appropriate measures (State of Washington, 1988).

Yet, in the same set of draft regulations, it is made explicit that the required long-term assessment of the chosen package of measures emphasize that program effectiveness is to be judged in terms of "trends related to water quality, habitat, biological conditions and land use".

How might proposed nonpoint source control measures be analyzed in a manner that explicitly accounts for the differences in the way such measures are perceived by policy planners, policy dispensers and the recipient population? More importantly, how might the elucidation of such differences be usefully incorporated into program design?

Measures that might be considered in a program to control nonpoint source inputs of fecal coliform bacteria -- a major pollutant concern in the shellfish growing areas of Puget Sound -- include the fencing of watercourses running through or adjacent to properties where livestock are kept, and the use of agricultural extension agents to advise property owners about the importance of proper livestock management and the means to effect it. These two measures represent qualitatively different approaches that would be perceived in different ways by the parties involved in the policymaking process. State level managers might embrace the idea of fencing farm animals away from bodies of water because they believe it has a reasonably good chance of reducing fecal coliform levels. Recognizing that it would be an onerous, high-cost endeavor for

local property owners, they might favor a regulatory approach with economic incentives. Property owners, however, seeing such a program as burdensome and unnecessarily intrusive, might become resistant to the idea of *any* regulatory program. In such a situation, local watershed committees would find themselves in the position of balancing the local political risks of recommending regulatory programs against the risks of being held accountable to higher authorities for taking directions not likely to be viewed as effective in reducing pollution loading.

A program of extension agent outreach, therefore, would offer the great advantage in the eyes of local planners and property owners of being voluntary, in terms of specific controls which might be recommended. It would also offer a number of perhaps less immediate benefits, such an an opportunity to gather, through field personnel visits, more information on the precise nature of pollution-generating activities in the district, and additionally projecting a positive image of an assistance-oriented bureaucracy. Higher-level authorities would, of course, perceive these same benefits, but might have more reason to be concerned that program effectiveness will ultimately depend on the willingness of property owners to adopt measures recommended by extension agents.

Because such regulatory initiatives as the PSWQA's draft regulations emphasize that effectiveness in protecting water quality is the criterion which must ultimately be served, top-down-oriented decision makers would be inclined to favor required property owner participation in whatever measures are adopted. They might then look to financial incentives and other mitigating measures designed to make such programs more palatable to their recipients.

In contrast, a "bottom-up" perspective on the same situation might attach more importance to maximizing the ability of local decision makers to interact effectively with property owners in important watershed areas. With such a perspective one might focus more on how levels of participation sufficient to fulfill policy objectives could be achieved in what are essentially voluntary programs.

Elmore (1984) adopts an economic perspective in suggesting that the effectiveness of such approaches will depend on whether consumer preferences for desired policy outcomes relative to other goods are really aligned with agency preferences. The assumption in choosing a voluntary approach, therefore, is that the information and/or assistance programs that comprise a voluntary approach will change behavior in the target population so that it reflects more closely what policy makers want. However, Harrington *et al.* (1985) suggest that people will not voluntarily alter their patterns of behavior unless, among other things, they are convinced that a) the policy objectives are worthy and the recommended actions will promote them, and b) the costs they will bear do not exceed the benefits they perceive they would accrue if the measures succeed.

Moving beyond a purely academic discussion of policy interactions in the nonpoint source control arena, what, then, are the practical considerations for policy makers at the state and local levels? What are the relevant lessons? A program which emphasizes the utilization of information on the perspectives of the different actors in the causal chain which implements policy in its design might consider steps like the following:

- Compile a comprehensive list of applicable nonpoint source pollution control measures that might be included in the program;

- Consider major groups with an interest in the watershed plan, and evaluate each measure from each perspective -- citing both strengths and weaknesses;

- Consolidate strengths and weaknesses by measure, in order to provide an overall summary of each measure;

- Focusing on weaknesses, evaluate how each might be reduced or ameliorated;

- Examine constraints that might affect efforts to address weaknesses in a program;

- Eliminate from further consideration those measures clearly incompatible with those constraints unlikely to be ameliorated by other actions which might be built into the program; and,

- Construct a program from the remaining measures, balancing the mandate for effectiveness against other watershed-specific constituent concerns.

This approach offers the advantages of explicit consideration of a number of perspectives, and a process that anticipates potential problems of program implementation. In this way, a more efficient and hopefully less adversarial policymaking procedure would be promoted.

V. Conclusions: Lessons for Puget Sound

It is, of course, premature to suggest that the PSWQA's proposed nonpoint source control program will run into implementation difficulties as it is applied to watersheds in the Puget Sound region. It can also be argued that the approach outlined here is intuitively obvious, and a structured restatement of the process as it in fact exists. Nevertheless, the early experience with rural nonpoint control in the region suggests that Agency planners would do well to adopt an implementation-focused perspective in anticipatory planning. As Shigenaka (1987) and Carter (1987) have documented, Washington Department of Ecology attempts to develop in 1984 a nonpoint program aimed at shellfish protection in the Burley-Minter watershed of south Puget Sound shifted in an uncontrolled fashion from a strongly regulatory approach to one that was heavily voluntary in character. The regulatory program initially proposed showed a predominant top-down approach to its design and implementation; predictably, it generated considerable local protest. The replacement program developed by a local citizens advisory committee, however, may have little in it likely to generate meaningful levels of citizen response to its campaign to increase public awareness of nonpoint source problems and solutions. An analysis of the program's effectiveness in reducing pollutants (Struck, 1986) has been rather pessimistic.

Implementation analysis focused on the delivery end of the policy process can anticipate implementation problems which, when unaddressed, serve either to render programs ineffective in achieving their goals, or to take control of program evolution effectively out of the hands of those with the greatest stake in having it succeed. Because such analysis is infrequently applied by decision makers in program design, most implementation studies to date have revealed after-the-fact consequences of implementation failures too late to do much for the programs which have failed. The approach described here offers one way to anticipate prospective problems rather than simply react to them. In the Puget Sound region, such a shift could result in efficient

crafting of more effective policies to address the ongoing challenge of nonpoint source pollution.

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SUMMARY STATEMENT

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Each of the papers presented here makes an extremely important point. Assimilative capacity must be brought out of the closet and examined specifically. In a world of scarce resources zero input or arbitrarily defined rules are not feasible because to garner support for pollution control policies it is important to be able to demonstrate the benefits that result from them exceed their cost.

In order to predict and estimate benefits that can be expected to flow from alternative policies we need better information. An important way to gather this information is to treat each policy change as an experiment - monitoring it as one would an experiment and thus comparing hypothesized with actual consequences. This approach, called adaptive management, enhances learning even if policies do not all achieve their intended results.

Policies can fail for a variety of reasons. One reason is that they are not implemented successfully. Historically most water pollution control measures have been engineering and technologically based, with implementation by well-trained professionals. As policies become more diverse and decentralized, and especially as successful implementation depends on the behavior of citizens (e.g. household toxics, land-use run-off, etc.) implementation becomes much more difficult. Thus, each policy must be examined not only in terms of its likely success if it is implemented successfully, but in terms of the likelihood of its being implemented successfully. This approach is called an implementation perspective. Assimilative capacity (or lack thereof) and accompanying benefit-cost analyses are also an important part of the implementation perspective because citizens and decentralized decision-makers must really support policies because they believe they are beneficial, something that they will not do if policy such as zero discharge is advocated as an end in itself without any evidence that benefits flow from such a policy.

Together the three papers presented in this section treat three very important issues in environmental decision-making.

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SHELLFISH CONTAMINATION

WHAT ARE THE SOURCES?

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U.S. Food and Drug Administration
Session Chair

Introductory Statement

Marleen M. Wekell*

Molluscan shellfish are highly regarded as a food in the United States. During the twentieth century many of the productive shellfish growing areas in the U.S. have been closed. Some of these closed are include the following (2): Boston Harbor, closed in 1909; San Francisco Bay, closed in the 1930's; Raritan Bay, closed in 1961; and parts of Chesapeake Bay, Narragansett Bay, and Puget Sound. These closures have been due to natural phenomena, overfishing, and/or pollution.

There are four major issues associated with shellfish safety. These are the presence of pathogenic microorganisms, marine toxics, chemical contaminants, and decomposition. The first three will be discussed today.

Before the talks in our session begin, let us review some relevant factors regarding shellfish contamination. First of all, shellfish are filter feeders. They feed by pumping water containing particulates through gill systems so that biological and chemical contaminants may be ingested if present. Second, shellfish grow in estuaries, often subject to contamination. Finally, shellfish are often eaten raw and whole.

The FDA provides administrative oversight regarding the regulation of shellfish in the U.S. Prior to 1925, the safety of shellfish for human consumption was evaluated by microbiological evaluation of the shellfish. This system was changed to evaluation of shellfish growing water after the 1924-1925 typhoid fever breakouts associated with consumption of law clams (1, 2). The National Shellfish Sanitation Program (NSSP) was formed at this time also. The NSSP is a voluntary cooperative program between the FDA, state shellfish control agencies and the shellfish industry. Shellfish growing waters are evaluated with the following guidelines (5):

1. There should be no nearby discharges of sewage containing human or animal waste.

2. The waters should be free of dangerous quantities of industrial wastes.

3. Paralytic Shellfish Poison (PSP) levels should not exceed 80 micrograms/100 gm of shellfish.

4. Coliforms should not exceed 70/100 ml water, and not more than 10% of the samples exceed 230/100 ml for a 5 tube MPN decimal dilution test.

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5. Fecal coliforms should not exceed 14/100 ml water, and not more than 10% of the samples exceed 43/100 ml for a 5 tube MPN decimal dilution test.

Since 1900, there have been approximately 11,600 cases of shellfish-borne disease in the U.S. and Canada (3). The cases can be broken down by percentage incidences into the following categories for the U.S. (3):

Gastroenteritis (unknown etiology)	-	43%
Typhoid (no cases reported since 1959)	-	26%
Infectious Hepatitis	-	11%
Norwalk Virus (1980-1986)	-	11%
Vibrio species	-	2%
Unspecified	-	7%

There are several other factors to consider regarding the contamination of shellfish by biological or chemical means. There is a need for better methods to evaluate bacteria in marine environments for most methods underestimate their numbers. Also there is new and intriguing evidence that marine bacteria can undergo a viable, but non-culturable phase (4). Some of these bacteria may play a role in formation of marine toxins. Also there are some "new" marine toxins besides PSP such as the one recently involved in the contamination of mussels in the area of Prince Edward Island in Canada. Indicator organisms and pathogens from humans versus animals in shellfish growing waters are also subjects of continued debate. There have been few studies regarding chemical contamination of shellfish and risks posed to humans consuming them.

Some of these issues will be discussed today. The five papers presented here will include discussions of potential pathogens, the microbiology of inshore and deepwater sites, fecal coliforms from harbor seals, microbiological and chemical contaminants in shellfish and PSP in shellfish of Puget Sound. Let us begin!

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INCIDENCE OF POTENTIAL PATHOGENS IN PUGET SOUND WATERS AND SHELLFISH

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Introduction

Many of the shellfish growing areas within the Puget Sound basin are subjected to pollution from nonpoint sources. These sources can and, in some cases, do contribute bacteria which have been traditionally considered as pathogens. Several of the small bays within Puget Sound, some used for harvest of oysters, *Crassostrea gigas*, are impacted by a variety of nonpoint pollution sources in the watershed such as septic systems, livestock, waterfowl, and wildlife.

Failing septic systems in some areas have been shown by analysis of water samples to contribute significant levels of fecal coliforms; in other cases, septic systems have been suspected as the cause of sporadic high bacteriological counts, but an actual cause and effect relationship could not always be demonstrated through analytical procedures or dye studies of the systems. In theory, the result would be the same in both cases. The area would be closed, to harvest without actual sources being determined if one were to interpret the National Shellfish Sanitation Program.

Therefore, the purpose of a recent study by the U.S. Food and Drug Administration and Washington State Department of Social and Health Services was to develop better methods to evaluate nonpoint pollution sources and, to gather more data on the incidence of pathogens in various estuaries where there were observable nonpoint pollution sources.

Materials and Methods

This study focused on two small estuaries within the South Sound basin, Eld Inlet and North Bay in Case Inlet. Streams, water from drainage ditches, shoreline sediments, and shellfish species were enumerated for total coliforms, fecal coliforms, fecal streptococci, *C. perfringens*, and heterotrophic count to

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determine sources. A qualitative assessment was made of samples for species of Yersinia, Aeromonas, Vibrio, and Salmonella. Sampling took place in May, 1986 (dry study), and March, 1987 (wet/winter). During March, 1987, well points or sampling tubes were placed in strategic locations to collect sub-surface water samples. It was thought that water from those well points might indicate possible fecal contamination not readily observable during a normal shoreline sanitary survey. All water samples were passed through membrane filters, either 250 or 500 ml portions, and the membranes were analyzed for pathogenic organisms.

Visual observation and historical shoreline information were used to select sampling stations during the study. These stations consisted of fresh water tributaries and areas demonstrating the following: underground seepage; organic buildup on the beaches indicated by algae growth; and silt layers which may enhance survival of bacteria versus sandy or gravel shorelines. Sampling sites within the watershed were chosen to determine additional impact.

Results

The bacteriological results confirmed that visual inspection and the historical sanitary survey information about the beach used to establish sample sites were, in some instances, of benefit. The samples as collected do demonstrate potential pollution to growing areas.

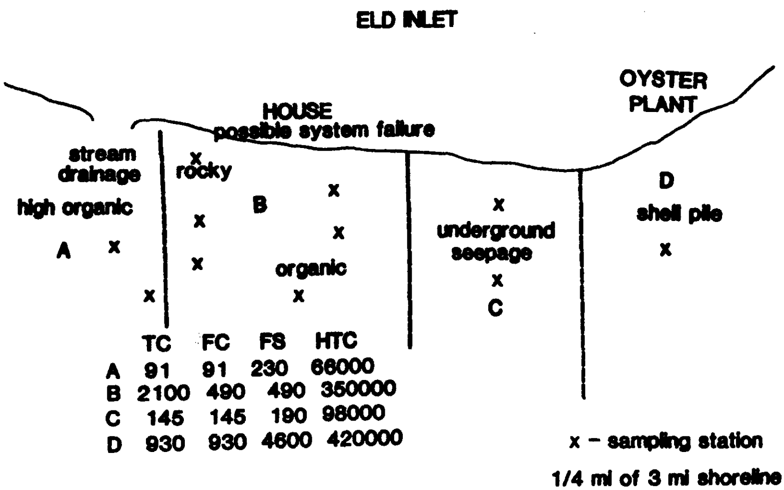

FIGURE 1. Results of shoreline sample stations based on visual observation in Eld Inlet showing diverse bacteriological content and possible impact from nonpoint pollution. (TC - total coliform, FC - fecal coliform, FS - Fecal streptococci, HTC - heterotrophic count.) Values are geometric mean of bacterial numbers for stations within each plot.

Figure 1 is an example of one of the areas that was found to have varying beach conditions and dramatic diversity in bacteriological content. It would appear then that nonpoint sources found on this particular beach can impact the adjacent growing area. Elevated heterotrophic, total and fecal coliform, fecal streptococci, (reported as geometric means of the sample stations within the plots on the beach) and *C. perfringens* counts were found in areas that appeared in most cases to have greater organic load.

A number of traditional pathogenic bacterial species were isolated from the shorelines. Table 1 presents the incidence of pathogenic species found during the two study periods. A seasonal, but contrasting, incidence is noted in two of the genera, *Vibrio* and *Yersinia*. Mesophilic *Vibrios* were more common in warmer months while *Yersinia* species were more prevalent during the winter or colder times of the year due to their psychrotolerant nature. We have found similar results in other studies done in Puget Sound. DNA hybridization analyses, using virulence marker probes, of species of these groups found none of the *Vibrios* to contain virulence factors. These two *Vibrio* sp. have not been historically shown to be related to fecal pollution. One isolate of *Y. enterocolitica* from the 260 tested was found to contain the virulence plasmid. It was

TABLE 1. INCIDENCE OF PATHOGENS IN TWO SOUTH SOUND SHELLFISH GROWING AREAS

	MAY 1986	MARCH 1987
Total Samples	140	131
V. cholerae, non 01	2.9%	0.08%
V. parahaemolyticus	15.0	0.02
Y. enterocolitica	17.1	33.6
Aeromonas sp.	90.7	84.7
C. perfringens	93.6	86.2
Salmonella sp.	0.02	0.02

isolated from a beach sediment below a house with a suspected failing septic system (the house shown in Fig. 1). Although a low incidence of pathogenic strains of Y. enterocolitica was found in the total population, the poential for contamination of the shellfish is evident. Y. enterocolitica was approximately 1/3 to 1/2 of the total Yersinia population in May and March respectively.

A high incidence of Aeromonas and C. perfringens was found during both studies. A seasonal occurrence was not evident. Potential pathogenic strains of Aeromonas were isolated from all sample types. Biochemical markers of virulence, including beta-hemolysins, were found in over 90% of the strains isolated. The Aeromonas group has been found from previous studies to be a common resident of aquatic environments. While C. perfringens has been previously used primarily as an indicator of fecal pollution from warm blooded animals, a recent study by Rhagubeer and Matches, at the University of Washington found that over 75% of the environmental strains they tested were capable of producing enterotoxin, the factor involved in human illness. Additionally, approximately 30% of their isolates were the same serotype commonly found implicated with human illness. Thus, we may have an organism with human health implications that should be looked at in a more serious light, particularly where other causative agents in shellfish illnesses cannot be identified.

Salmonella serogroup C_1 was isolated from sediment at the same sample site in one bay during both studies. This suggests a continual source of this pathogen during a nine-month period. Although not proven, the presence of a hobby farm with ducks/geese appeared to be the source of this pathogen. The presence of Salmonella of the same serogroup in a small fresh water stream near the farm and on the shoreline below indicates a direct and continued source of contamination to the shellfish growing area.

Conclusions drawn from the study are:

(1) Bacterial species that have been traditionally classified as human pathogens can be found in areas impacted by nonpoint pollution.

(2) Bacteriological analysis of sediments can be supportive of visual shoreline appearance.

To confirm the above findings and the conclusions drawn from this study would require additonal sampling as per NSSP criteria. Samples would be collected during the most adverse pollutive and hydrographic conditions. In the Puget Sound area, this would be during a high rainfall period which would charge the ground water system coupled with moderate tidal excursion.

Microbiology of Inshore and Deep Water Environments of the Seahurst Area of Puget Sound

Dr. Jack Matches*, Steve Fischnaller, Errol V. Raghubeer and Denise Anderson

INTRODUCTION

This paper is a report of work done between July 1982 and March 1984. Data collected during this 21-month study was designed to obtain pre-discharge ecological data for a planned expansion of the Renton Sewage Treatment plant. The planned discharge into Seahurst Bay was changed and the final site chosen was from Duwamish Head into Elliott Bay. These microbiological studies, a part of a large study, were directed towards environmental health aspects and, we studied indicator organisms and pathogens.

Bacteria are continually discharged into Puget Sound from a number of sources. These include municipal sewage treatment plant effluent; sewage treatment plant overflow; industrial waste; storm water runoff; private sewage discharges in the form of septic tank leakage; farm waste and resident animal waste. While most sewage-associated bacteria are harmless to humans, a small but significant portion are known human pathogens.

The presence of pathogenic and indicator bacteria in the marine environment can have a direct relationship to human health. There is limited contact between humans and most of the offshore water column; however, much more contact occurs between humans and the intertidal areas. When pathogenic bacteria and viruses are present in the intertidal zone, human exposure may occur through several activities including beachcombing, shellfish harvest and consumption, fishing, swimming in warmer months, and scuba diving throughout the year. The presence of pathogenic organisms in the intertidal zone can thus pose a public health hazard to users of these areas. Contact between humans and the Puget Sound basin is limited and through fish harvested from the area.

When pathogenic bacteria, originating in the gut of man or other warm-blooded animals, are present in the water column and intertidal waters in numbers too low for reliable detection, the indicator organism concept becomes important. These indicators are also found in the gut of man and other warm-blooded animals but in much higher numbers than pathogenic bacteria. When these indicators of fecal pollution (fecal coliforms, enterococci and Clostridium

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perfringens) are found in water and shellfish samples, the potential for the presence of enteric pathogens is high.

Sampling Stations

Intertidal sampling stations used in this study are shown in Figure 1. The beaches shown include Lincoln Park, Seahurst Park, Normandy Park, Des Moines-Vashon Ferry, NE Vashon Park, Tramp Harbor and Robinson Park. Also, note the indicated sewage disposal outfalls in or near the sampling area. The sampling areas for water, fish and sediments are shown in Figure 2. Water column stations are numbered from 1 to 13. Stations 4-10 and 12 and 13 were used in this study.

Sample Descriptions

Samples collected and analyzed during this study are shown in Table 1. Intertidal samples of water, shellfish and sediment were collected on a monthly basis from the beaches on the east side of Puget Sound. Additional samples were collected on a quarterly basis from the four sites on Vashon Island.

Water column samples were collected on a monthly basis from five of the nine stations per month. Basin sediments were collected only once during this project. Fish intestinal content samples were collected on a quarterly basis during the last half of this project. Fish and sediments were collected from the basin area shown in Figure 2.

Bacteria isolated during this study were different for each type of sample collected but included fecal coliforms, *Yersinia enterocolitica* and *Salmonella* for shellfish. Intertidal water samples were monitored for the presence of fecal coliforms, enterococci and *Salmonella*. Intertidal sediments collected in the same area as the clams were monitored only for the presence of *Clostridium perfringens*. In the water column, samples collected at one meter depth were measured for the presence or numbers of indicator organisms (fecal coliforms) and pathogens (*Yersinia enterocolitica* and *Salmonella*).

Basin sediments were analyzed for the presence of the indicator and pathogenic organism *Clostridium perfringens* to produce baseline data which characterizes the accumulated fecal pollution in these areas. Fish intestinal contents were also analyzed for *Clostridium perfringens* to measure the potential pick-up of fecal pollution from the fish feeding areas.

RESULTS AND DISCUSSION:

Results are presented on the microbiology of samples collected from the intertidal area, the water column and sediment and fish gut contents. A total of 707 samples were collected and analyzed during this study.

Intertidal

Intertidal beaches are used for the harvest of shellfish. Since shellfish are filter feeders they will pick up bacteria from the water and are thus indicators of the sanitary conditions of the water. In addition, since shellfish are often given very mild heat treatments during cooking, the bacteria present may not all be killed. In this study, clams were the primary shellfish species present. In other areas of Puget Sound, oysters are the predominant shellfish species harvested and consumed, and often without cooking. In fact, oysters are the only animal eaten alive. Therefore, animals eaten alive or undercooked could be the source of potential pathogens for consumers.

The levels of fecal coliforms in intertidal water are shown in Figure 3. Numbers enumerated by the most probable number method (MPN) vary between less than 10 to almost 200 per 100 ml of water. The significance of these data is that six of the beaches sampled had fecal coliform levels higher than the Food and Drug Administration guidelines permit for commercial harvest. The guidelines for shellfish growing waters permit a maximum mean of 14 fecal coliforms per 100 ml with not more than 10% of the samples exceeding 43/100 ml. Although these beaches are not used for commercial harvest, they do support private or recreational harvesting. The levels of fecal coliforms indicate that potential pathogens may be present. This indicator concept does not mean that if fecal coliforms are high, pathogens will be present. The usefulness of the concept is that if fecal coliform levels are low, the chance for the presence of pathogens is also low.

The levels of fecal coliform bacteria permitted (by the guidelines) in shellfish at the wholesale level are 230/100 grams meat by the MPN procedure. Since water samples had high numbers of fecal coliforms, it is not surprising that clams also exceeded the guidelines for commercial harvest as shown in Figure 4. Beaches with intertidal water not meeting the shellfish harvest guidelines were also the beaches with high numbers of fecal coliforms in the shellfish. The numbers in shellfish were higher than numbers in water. This difference was due to the filter feeding by clams. In pumping water the clam was able to filter and concentrate the bacteria.

Clams were tested for the presence of _Yersinia enterocolitica_ and data obtained are shown in Table 2. _Yersinia_ is not an indicator of fecal pollution. Instead _Yersinia enterocolitica_ is a human pathogen and has been implicated in food borne disease. Since _Y. enterocolitica_ and _Y. enterocolitica_-like organisms can only be distinguished through biochemical testing (or gene probes when available) and not by colony appearance on selective plating media, the MPN values collected during the study were a combination of the four species. After identification, actual numbers were calculated. Over 400 cultures of _Yersinia_ were isolated from clams and 162 or 38% were identified as _Y. enterocolitica_. The three other species, _intermedia_, _frederiksenii_ and _kristensenii_ made up the remainder (Table 3).

A seasonal fluctuation in numbers of *Yersinia enterocolitica* is evident from Table 2. During the colder months of January through March when water column temperatures dropped to 8.5°C, 38 of 49 shellfish samples (78%) were positive, whereas only 4 of 50 samples (8%) were positive from July through September when water column temperatures peaked at 15°C. The effects of temperature on *Yersinia* numbers are shown in Figure 5. As the water temperature decreases, the numbers of *Yersinia* increase. This inverse relationship also holds true at higher water temperatures.

Yersinia enterocolitica are entering the environment throughout the year but are present in higher numbers during cold weather. This seasonal increase has not been explained but may be due to prolonged survival of the organisms, or they may be introduced to the marine environment in greater numbers during the winter months.

The numbers of salmonella isolated in these studies (Table 3) were low. Only one isolate was recovered and identified from 104 clam samples tested. Also only one isolate was recovered from 102 intertidal water samples. Both come from the area of Vashon Island. Also, this pathogenic bacterium was not isolated from the 66 water column samples tested.

Salmonella are enteric pathogens which are excreted in high numbers from patients suffering from salmonellosis. During salmonellosis outbreaks involving large numbers of people, the levels of these pathogens can increase in sewage. During other periods, the numbers discharged in sewage are reduced greatly by dilution and short survival in the marine environment. The levels isolated in these studies was low. Only two samples out of 272 tested were positive for *Salmonella*. Data reported during the last few years indicate that pathogens and other bacteria may be present in the environment but not culturable. Although not tested, this may have happened in this study.

Clostridium perfringens were isolated from both shellfish and intertidal sediment (Figure 6). Numbers varied between about 18 and 65 per gram of shellfish tissue and between 9 and over 100 per gram of intertidal sediment. These bacteria which are both pathogens and indicator organisms show that fecal material has reached the environment. They are present in the sediment and also in the clams which are consumed. Data from our studies and that reported by other workers show that *C. perfringens* are present in the environment as spores. This partially explains the numbers in the environment. In addition to reaching the environment in high numbers, the resistant spores permit the organism to remain viable for long periods of time. This was borne out with short term viability studies in soil from our earlier work.

Enterococci or fecal streptococci are gut organisms often used as indicators of fecal pollution. As with the other indicator bacteria, when found in the environment, they indicate fecal contamination and the potential presence of pathogenic bacteria (Figure 7). Enterococci are present in the intestinal tract in

lower numbers and die off more slowly than fecal coliforms. The enterococci also do not normally multiply in water.

Published data show that when the levels of enterococci increase in marine recreation waters to levels of 10 or more per 100 ml, the rate of gastrointestinal symptoms among swimmers increases. Enterococci levels in this study exceeded 10 per 100 ml in the same sampling areas where fecal coliforms were high, a further indication of fecal contamination.

Water Column

Stations, numbers 6, 12 and 13, are the only water column sites with mean MPN fecal coliform values that exceed 14 per 100 mls of water (Figure 8). Station number 6 is located approximately 0.1 mile from the Salmon Creek sewage discharge point. Pollution sources causing an increased fecal coliform density at stations, numbers 12 and 13, were unidentified.

The differences between fecal coliforms in offshore and intertidal water are not clear. However, fecal sources in intertidal areas may be runoff, small streams, shore birds as well as particular matter moved to the intertidal areas by wind and tidal currents. Offshore water, which is deep may undergo mixing with dilution of the numbers of bacteria even through sewage disposal outfalls are in the sampling area. In our portion of the study we did not trace the sources to their origin but rather measured the organisms present at the sampling stations.

The presence of *Yersinia enterocolitica* in the water column was measured. Only one out of 76 water column samples was positive for this pathogen. The positive sample was collected in December. In addition, only one water sample, collected in January, was positive for *Y. enterocolitica*-like species. The water column samples, due to dilution, contain lower numbers of organisms than shellfish because of the concentrating effects of the shellfish's filter feeding method.

Yersinia enterocolitica are present in higher numbers in the inshore areas than the water column. This may be related to the proximity of the inshore sampling sites to potential sources of contamination.

Sediments and Fish Guts

Marine basins have been shown to act as receiving troughs for particulates settling out of the water column. In water systems that are subjected to large volumes of sewage effluents, such as Puget Sound, the bacterial load which settles out with the particulates increases tremendously. Also, literature data show that a close relationship exists between the amount of sewage pollution and the levels of *C. perfringens* in marine basin sediments. In this study the levels of *C. perfringens* enumerated from basin sediments at the shallowest depth tested (61 meters) was 763 cells/gram, whereas an average of 15,867 *C. perfringens*

cells/gram were enumerated at the deepest location of 191 meters (Figure 9).

The higher numbers of C. perfringens in the basin sediments, although affected by pollution levels, may also be influenced by the temperature regime in the deeper waters. Spores and possibly vegetative cells may survive longer in the deeper regions because the temperature is lower and more stable than temperatures at intertidal sites. Since high numbers of C. perfringens were found in sediments showing a concentration of fecal material, we examined the gut contents of fish collected between 50 and 200 meters depth. In previous published work, we found that the numbers of C. perfringen in fish gut contents varied depending upon the levels of pollution in the sampling areas. In that study, the area off the end of the diffuser pipe at the West Point outfall contained high numbers of C. perfringens. As we traveled north through Puget Sound and then out the straights of Juan De Fuca the numbers decreased.

In this study (Figure 10) the numbers of C. perfringens from fish varied from approximately 90 organisms per gram of gut contents at Tramp Harbor to over 446 organisms per gram of gut contents at the Seahurst sampling station.

We feel that the high levels of C. perfringens in fish gut contents is indicative of the fecal material in the basin and this material is picked up by fish probably during foraging.

As a summary of C. perfringens work, the data in Figure 11 show the variation in numbers between types of samples collected.

Hundreds of C. perfringen isolates were collected during these studies and 90 were sent to the Center for Disease Control in Atlanta, Georgia for serotyping (Figure 12). These included isolates from intertidal as well as basin areas. CDC was able to serotype approximately 50% of our isolates which was greater than the approximately 40% they routinely type from clinical samples. These serotyped organisms fell into 30 different serotypes that contain strains causing food poisoning and other health problems in humans.

Some strains of C. perfringens produce enterotoxin which is responsible for food poisoning in humans. We developed an enzyme linked immunosorbent assay (ELISA) technique to determine the levels of enterotoxin produced by selected isolates including those serotyped (Figure 13). Many of the isolates collected in this study produced enterotoxin and those from the basin produced the highest levels.

We conclude from these basin studies that contamination is coming primarily from municipal sewage effluent discharges, with the higher numbers of organisms being correlated with closeness to the sewage outfalls. Serotyping of isolates indicate that strains of C. perfringens that cause human food poisoning are present in the marine environment. Some of these bacteria could conceivably have been excreted in feces by individuals suffering from perfringens

gastroenteritis. Also, a less likely conclusion is that they are naturally present in the environment. This relationship may be measured when a rapid serotyping procedure is available for environmental strains of _C. perfringens_.

CONCLUSIONS

The conclusions drawn from these data show several things.

1. An area we originally thought to be pristine was in fact impacted by pollution.

2. Some of the sources of pollution were not obvious until we found that water reaching the sampling areas could be influenced by 9 different sewage outfalls close to the sampling sites.

3. Levels of fecal coliforms in intertidal areas were above the guidelines permitting commercial shellfish harvest. Counts were high in the growing waters as well as in shellfish.

4. Although data were not presented, _Vibrio parahaemolyticus_ was not present in high numbers in samples due possibly to cold water temperatures. It is common for these organisms to reach high numbers in shallow bays where water temperatures increase. However, along the main body of Puget Sound which is deep with mixing the temperatures do not increase to levels permitting vibrio to increase rapidly.

5. _Salmonella_ an enteric pathogen were detected in only two samples. Low numbers may be a result of low levels added to the environment, failure to survive in the marine environment or the presence of unculturable salmonella.

6. _Clostridium perfringens_, one of the most widely spread pathogens is also an indicator organism. It measures past and present fecal contamination. This organism was found in all samples we tested.

7. The _C. perfringens_ isolated from fish gut and basin sediments showed a higher proportion of enterotoxin production (% of population), than from intertidal areas.

8. The _C. perfringens_ from the deep area also produced higher levels of enterotoxin than isolates from intertidal areas.

9. We feel that the disposal of sewage accounts for the presence of high numbers of _C. perfringens_ in the basin areas.

10. The organisms in the intertidal and water column areas may come from sewage particulate matter floating to the surface and moved by wind or currents. In addition, organisms in the intertidal area can be contributed by sources from land such as runoff and streams contaminated by humans or animals.

TABLE 1: Total number of samples examined

SAMPLE TYPE	TOTAL NUMBER OF SAMPLES COLLECTED
SHELLFISH	178
INTERTIDAL WATER	166
INTERTIDAL SEDIMENT	178
WATER COLUMN	106
BASIN SEDIMENT	18
FISH INTESTINAL CONTENTS	61

TABLE 2: Incidence of Yersinia enterocolitica sensu stricto in shellfish

		Months sampled																				
	n	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Lincoln Pk.	25	-	-	-	-	-	-	+	-	+	+	-	-	-	-	-	+	-		-	+	-
Seahurst Pk.	42	-	-	-	+	-	-	+	+	+	-	+	-	+	-	-	-	+		-	+	+
Normandy Pk.	40	-	-	-	-	+	-	+	+	+	+	+	+	-	-	-	-	+		+	+	+
Des Moines Bch.	38	-	-	-	+	+	+	+	+	+	-	+	+	+	-	+	+	+		+	+	+
Vashon Ferry	6	-						+			-			-			-				+	
NE Vashon Pk	6	-						+			-			-			-				+	
Tramp Harbor	6	-						+			-			-			-				+	
Robinson Pk.	5	-									-			-			-				+	

TABLE 3: Species distribution of <u>Yersinia</u> isolates

Yersinia enterocolitica	162 (39%)
Yersinia intermedia	122 (29%)
Yersinia frederiksenii	85 (20%)
Yersinia kristensenii	23 (5%)
Other	27 (6%)
Total	419

TABLE 4: Number of samples positive for Salmonella

SAMPLE TYPE	N*	NPOS**	% POSITIVE	COLLECTION SITE OF POSITIVE SAMPLES
SHELLFISH	104	1	<1%	N.E. VASHON PARK
INTERTIDAL WATER	102	1	<1%	VASHON FERRY
WATER COLUMN	66	0	0%	

*N = NUMBER OF SAMPLES ANALYZED

**NPOS = NUMBER OF SAMPLES YIELDING POSITIVE RESULTS

FIGURE 1: Beach sampling station

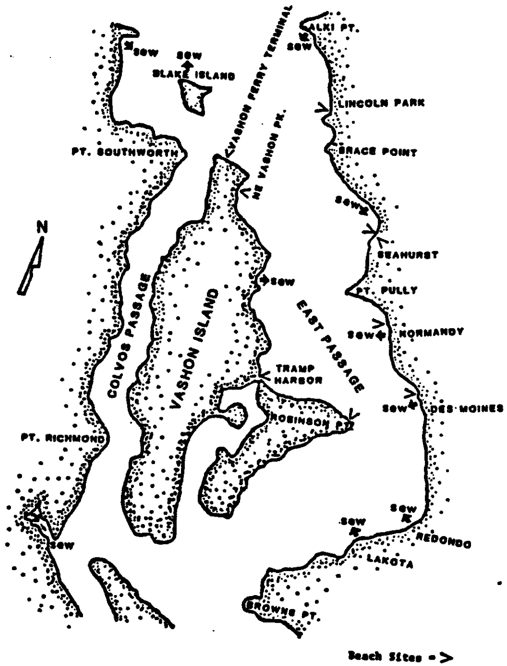


FIGURE 2: Water column sampling stations

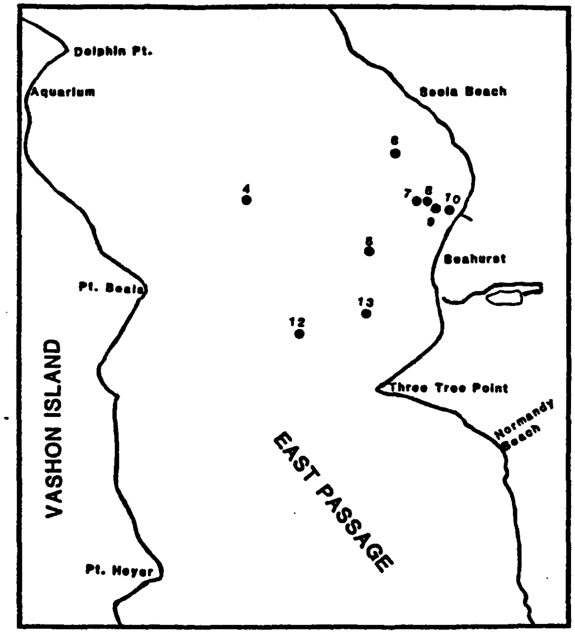


FIGURE 3: FECAL COLIFORMS IN INTERTIDAL WATER

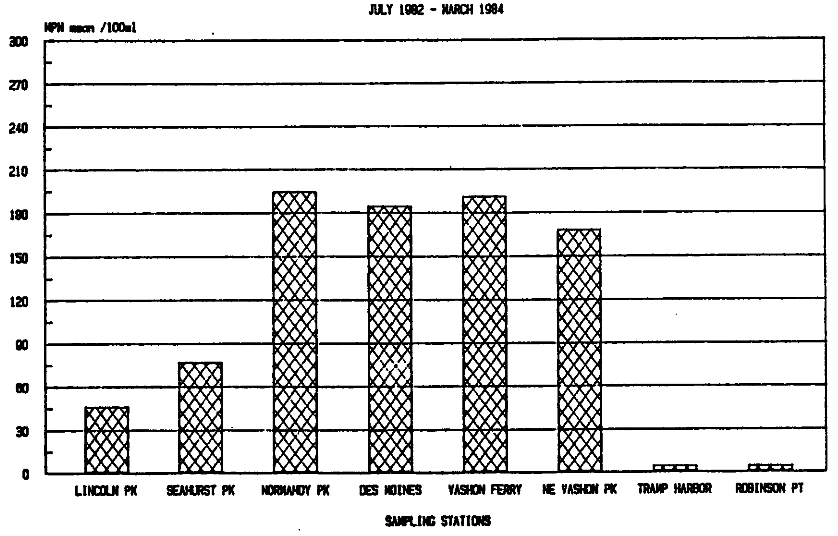


FIGURE 4: FECAL COLIFORMS IN SHELLFISH

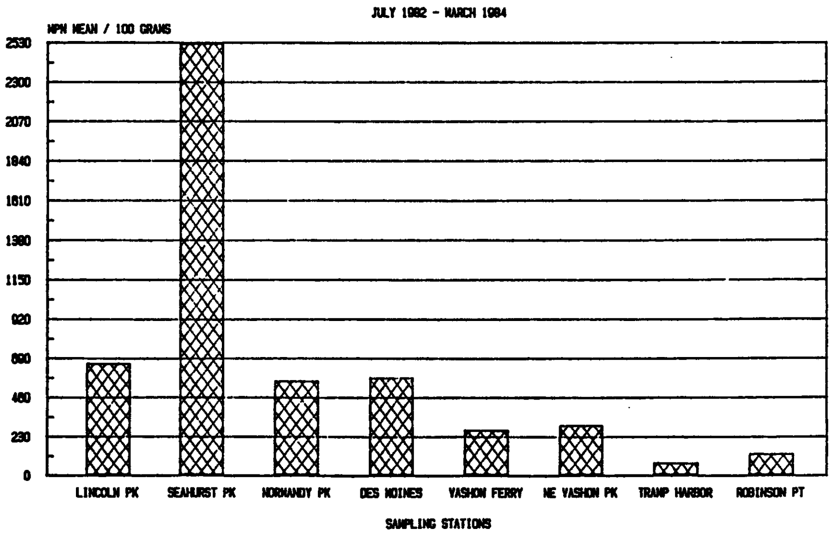


FIGURE 5: YERSINIA ENTEROCOLITICA VS TEMPERATURE

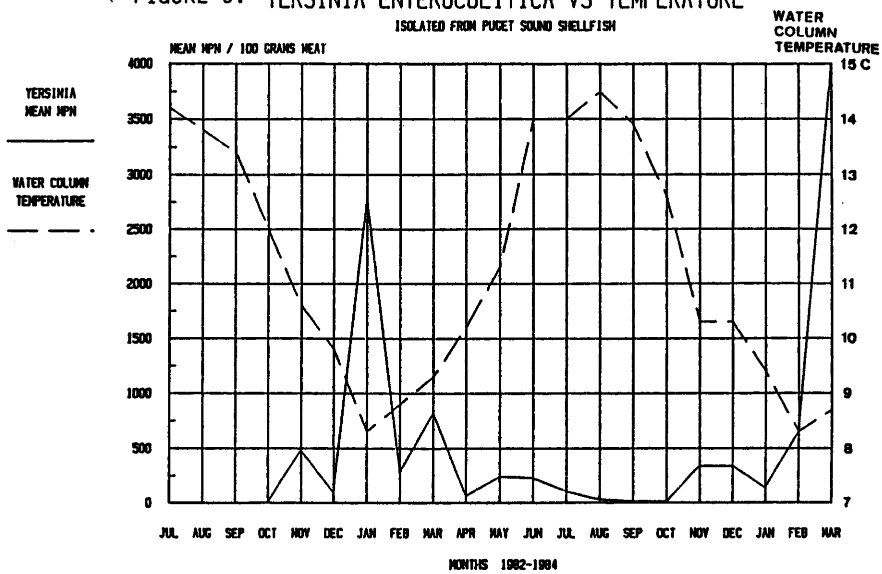


FIGURE 6: INTERTIDAL Clostridium perfringens

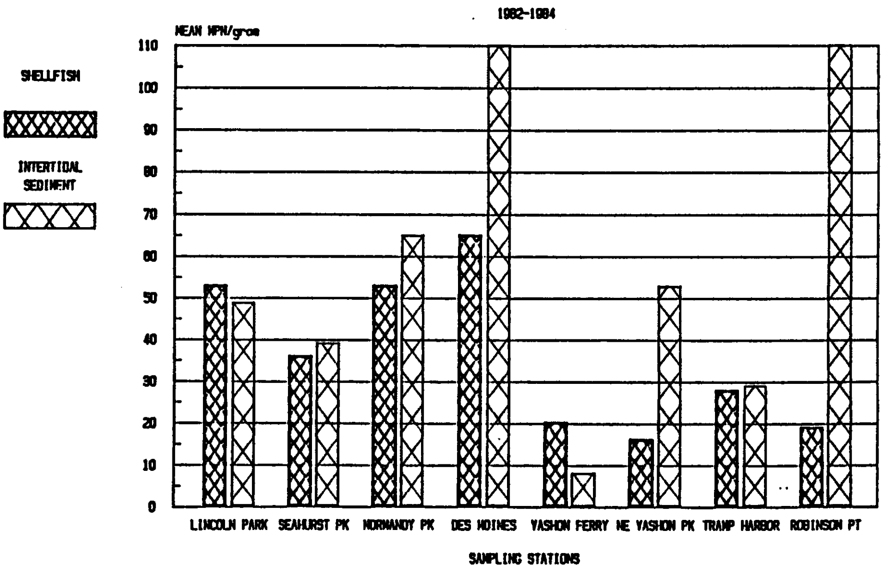


FIGURE 7: ENTEROCOCCI IN INTERTIDAL WATER

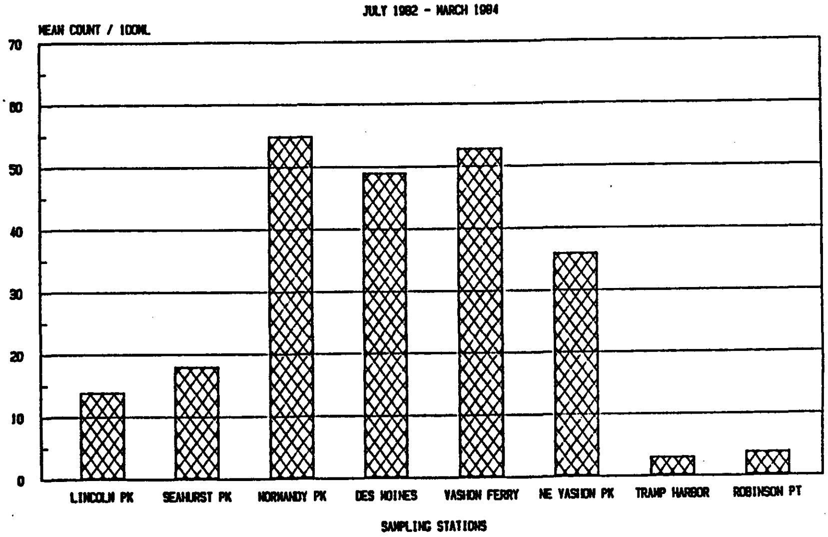


FIGURE 8: FECAL COLIFORMS IN WATER COLUMN

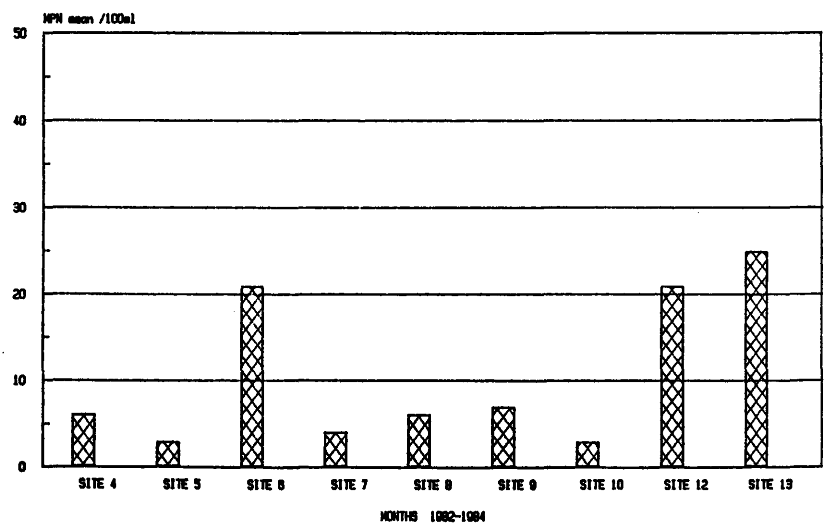


FIGURE 9: Clostridium perfringens - BASIN SEDIMENT

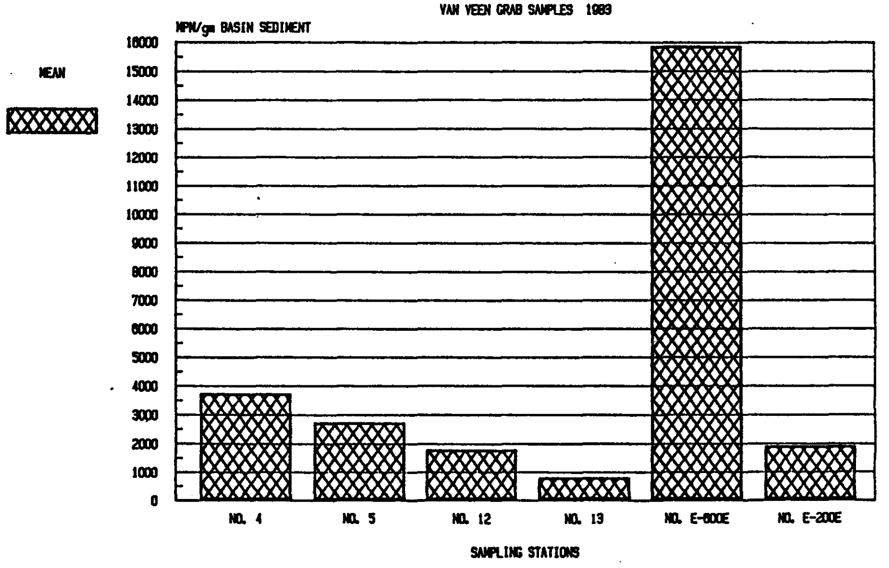


FIGURE 10: Clostridium perfringens IN FISH GUT

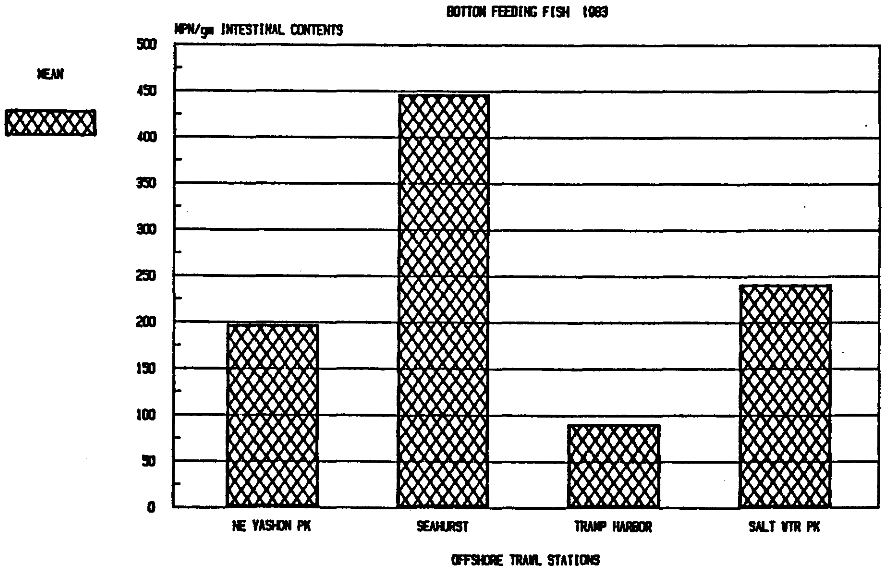


FIGURE 11: LEVELS OF C. PERFRINGENS IN ENV. SAMPLES

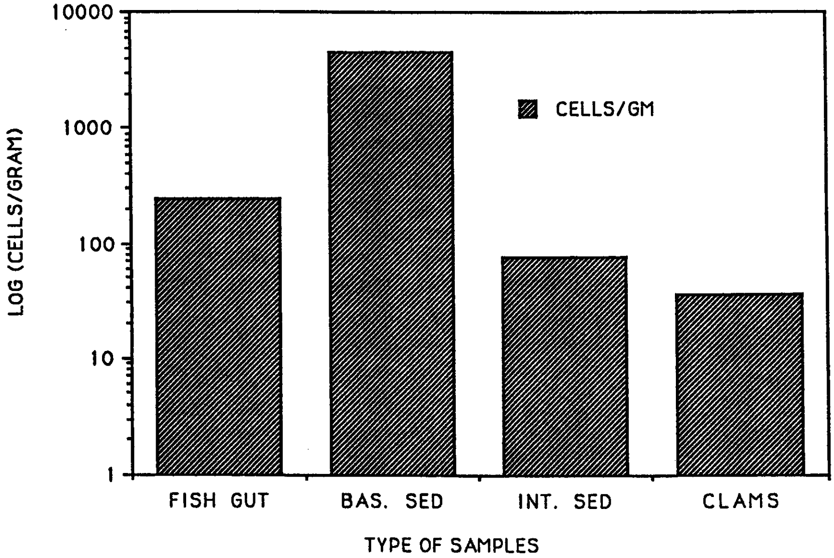


FIGURE 12: SEROLOGY OF C. PERFRINGENS

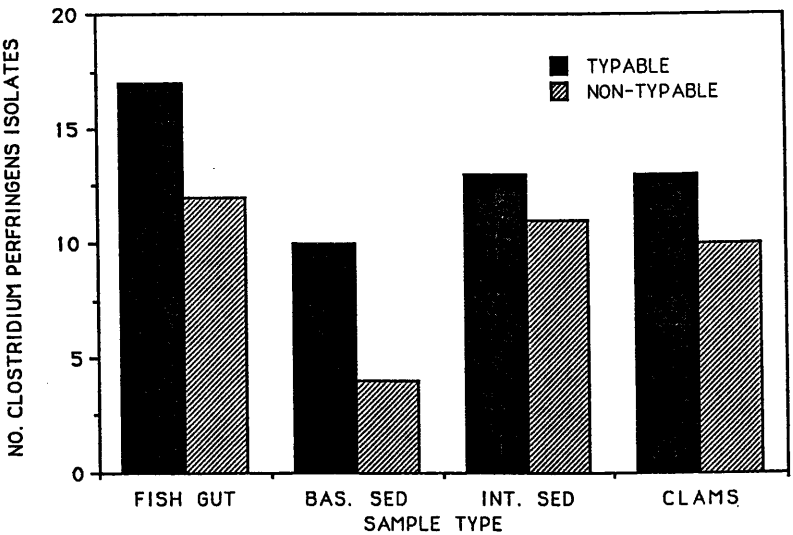
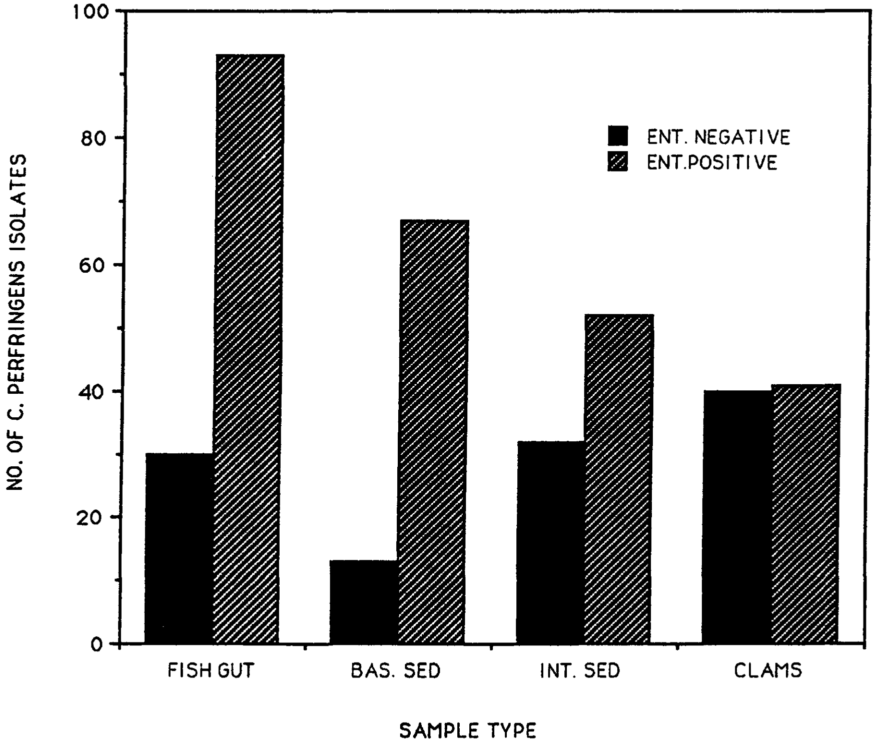


FIGURE 13: ENTEROTOXIGENICITY OF ISOLATES



Harbor Seal Populations and Their Contributions to Fecal Coliform Pollution in Quilcene Bay, Washington

John Calambokidis* and Brian D. McLaughlin*

Introduction

Fecal coliform bacteria are found primarily in the intestines of warm-blooded animals and are currently used as an indicator of bacterial contamination of marine and fresh waters (Geldreich 1966). Commercial harvesting of shellfish in the headwaters of Quilcene Bay has recently been closed due to high fecal coliform levels (Cook 1984, 1985). Humans and domestic animals have traditionally been considered the primary sources of bacterial contamination with remedial action usually focused on these sources.

Harbor seals congregate in many areas of Puget Sound, including Quilcene Bay (Calambokidis et al. 1978, 1979, 1985). Very little data exist on the possible contribution of marine mammals to fecal coliform levels found in marine waters.

We monitored the number of harbor seals in Quilcene Bay, estimated the amount of feces they generate, and examined coliform concentrations in their feces in order to evaluate the possible contribution of harbor seals to fecal coliform levels found in Quilcene Bay.

Methods

Censuses of harbor seals in Quilcene Bay were conducted at least once a month from September 1985 to October 1986. Counts were also made during this period at the Dosewallips River Delta, just south of Quilcene Bay.

Seal haul-out sites in Quilcene Bay and the Dosewallips Delta were searched for seal scat for fecal coliform analysis. Ten samples of fresh feces were collected and delivered on ice to Biochem Environmental Services, Inc. within 7 hours.

Concentrations of total coliform, fecal coliform, and fecal streptococci were determined using the Most Probable Number (MPN) method. Samples were tested for the predominant bacterial populations and the presence of human pathogenic enteric organisms through Salmonella and Yersinia enrichment.

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Seal feces were also examined to determine the food consumed by seals. Feces used for fecal coliform analysis as well as other scats collected previously were screened through nested 0.5 and 2.0 mm screens. Fish otoliths recovered from the scats were compared to a reference collection at Cascadia Research and the species of fish identified.

Results and Discussion

Harbor seal populations

Numbers of harbor seals counted at Quilcene Bay on 56 days ranged from 0 to a maximum of 230 seals. Seals were primarily found hauled out at log booms on the eastern side of Quilcene Bay. Lower numbers were found intermittently hauled out on oyster rafts at the southeast entrance of Quilcene Bay. Monthly high counts were variable and there were no apparent seasonal trend in numbers (Figure 1). The overall harbor seal population in Quilcene Bay likely fluctuates with animal movement in and out of the bay. The high count of 230 seals is considered the maximum number of seals present in the bay at any one time. The number of seals seen at the Dosewallips River Delta, just south of Quilcene Bay, often exceeded the counts in Quilcene Bay, with a maximum of just under 500 animals seen at this site.

Harbor seal populations in Quilcene Bay and the neighboring Dosewallips Delta appear to be increasing based on comparison of counts made from 1977 to 1986. Numbers of seals seen at the Dosewallips Delta in this period have more than doubled while those

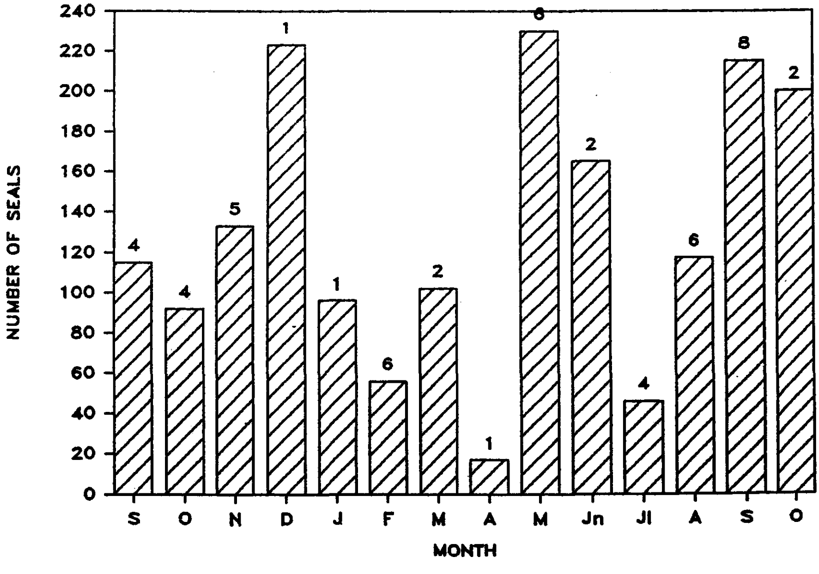

Figure 1. Monthly high counts of harbor seals in Quilcene Bay, September 1985 to October 1986. Number of days counts were made each month is listed.

in Quilcene Bay have increased at a slower rate. Harbor seal populations in other parts of Puget Sound have been growing rapidly in recent years as well. The rate of increase seen in Quilcene Bay appears to be lower than for many other areas in Washington State (Calambokidis et al. 1985). In 1972 harbor seals were protected under the Marine Mammal Protection Act. This year probably marks the most likely time when harbor seal populations began to increase.

Scat production

Daily seal fecal production can be estimated in two ways. First the average feces weight found in this study of 183 g can be multiplied by two (estimated defecations per day), yielding an estimated 366 g per day per seal. Alternately feces production can be estimated from food consumption and assimilation efficiency. Feces weight in seals has been reported to be around 10% of fish weight (Pastukhov 1974, Ashwell-Erickson and Elsner 1981). Estimated daily fish consumption rates for harbor seals vary widely with most common estimates between 5 and 10% of body weight (see summary in Ashwell-Erickson and Elsner 1981 and Calambokidis et al. 1984). A mathematical model (Leslie matrix) of a harbor seal population structure was used along with harbor seal weight-age equations provided by Boulva and McLaren (1979) to determine the average weight of a seal in a population growing at 5% per year. The mean weight of a harbor seal was 50 kg based on these calculations. The daily scat production of a typical 50 kg seal can thus be estimated as 50 kg X 0.05 to 0.10 (consumption) X 0.10 (fecal/fish weight) = 250 to 500 g. This range of calculated rates brackets the estimated fecal production from the first technique described above.

Using the fecal production rates above the maximum number of 230 seals seen in Quilcene Bay would produce approximately 57 to 115 kg of feces per day.

Ashwell-Erickson and Elsner (1981) reported that prey consumption and assimilation rates may vary depending on prey. The only prey identified in scats collected during this study were of Pacific hake.

Bacterial speciation

The predominant bacterial population, i.e., those organisms comprising the upper 10% of the population included Bacillus species, *Escherichia coli*, Klebsiella, Edwardsiella, Streptococcus, Staphylococcus, and Micrococcus. The two types of Streptococci recovered were unusual in that one was a beta-hemolytic pyogenic form and the other a non-hemolytic form not fitting Sherman criteria.

Three types of *E. coli* were found. The conventional form conforming to typical biochemical patterns, a more rare anaerogenic form, and a type exhibiting an unusual carbohydrate utilization pattern: positive in lactose, mannitol, and rhamnose while negative in sucrose, salicin, and dulcitol.

No human enteric pathogens were isolated from either the Salmonella or Yersinia enrichment procedures. Organisms recovered included

species of Proteus, Citrobacter, Pseudomonas, and Aeromonas. We know of no reports that have identified Salmonella from the tissues or feces of harbor seals. Salmonella was not among the various bacteria found in tissue samples and swabs from dead or dying harbor seals in Washington State (Calambokidis et al. 1985). Salmonella has been found in the tissues of other pinniped species (Keyes 1965, Anderson et al. 1979, Stroud and Roelke 1980) and is likely present in some portion of the harbor seal population.

Fecal bacteria concentrations

Fecal coliform concentrations in the 10 seal feces examined ranged widely from 4.0×10^6 to 9.2×10^8 per g with a median and geometric mean of 2.7×10^7 and 3.1×10^7, respectively. Geldreich (1976) and Mara and Oragui (1981) list fecal coliform concentrations in the feces of humans and a variety of wild and domestic animals (Table 1).

Table 1. Median and geometric mean fecal coliform concentrations per gram for different species reported in the literature and found in this study.

	Geldreich (1976)		Mara and Oragui (1981)			
Fecal source	# samples	Median	# samples	Geometric mean	Min	Max
Human	43	1.3×10^7	18	6.3×10^7	1.3×10^5 -	9.0×10^9
Cattle	11	2.3×10^5	8	1.0×10^6	1.5×10^5 -	6.5×10^6
Sheep	10	1.6×10^7	7	2.7×10^6	1.8×10^5 -	5.6×10^7
Pig	11	3.3×10^6	8	3.9×10^7	4.9×10^6 -	6.0×10^8
Horse	-	1.3×10^4	5	1.0×10^3	6.3×10^2 -	3.4×10^3
Duck	8	3.3×10^7	5	2.0×10^7	8.8×10^6 -	4.9×10^7
Chicken	10	1.3×10^6	9	6.3×10^6	3.7×10^6 -	1.5×10^7
Turkey	10	2.9×10^5	6	7.9×10^8	2.6×10^8 -	2.0×10^9
Goose	-	-	3	6.3×10^3	9.7×10^2 -	6.6×10^4
Cat	19	7.9×10^6	5	6.3×10^7	8.9×10^4 -	2.6×10^9
Dog	24	2.3×10^7	5	5.0×10^8	4.1×10^6 -	4.3×10^9
Rabbit	14	2.0×10^1	4	1.0×10^4	2.8×10^3 -	4.9×10^4
Mouse	7	3.3×10^5	4	6.3×10^6	4.7×10^6 -	1.0×10^7
Rat	2	1.8×10^5	4	1.6×10^5	5.6×10^4 -	6.3×10^5
Gull	-	-	6	6.3×10^3	1.7×10^2 -	2.7×10^5
Chipmunk	3	1.5×10^5	-	-	-	-
Elk	32	5.1×10^3	-	-	-	-
Robin	-	2.5×10^4	-	-	-	-
Eng. sparrow	-	2.5×10^4	-	-	-	-
Starling	-	1.0×10^4	-	-	-	-
Red-wing. bl.	-	9.0×10^3	-	-	-	-
Pigeon	-	1.0×10^4	-	-	-	-
This study						
Harbor seal	10	2.7×10^7	10	3.1×10^7	4.0×10^6 -	9.2×10^8

Concentrations for the same species vary greatly (up to five orders of magnitude) and the median values reported by Geldreich (1976) are often an order of magnitude different from the geometric mean values for the same species reported by Mara and Oragui (1981). Despite these variations some general comparisons can be made between other species and seals. The geometric mean concentration we found in seals (3.1×10^7) is lower than the geometric mean concentration reported for humans by Mara and Oragui (1981) but higher than the median value reported by Geldreich (1976). Fecal coliform concentrations of seals were generally higher than for most domestic animals but similar to dogs, cats, pigs, and ducks.

Concentrations of fecal streptococcus were much lower than for fecal coliforms and ranged from 4.3×10^2 to 9.3×10^4. The fecal coliform to fecal streptococcus ratio ranged from 114 to 767,000. A high ratio of fecal coliform to streptococcus is considered more typical of human feces than those of domestic animals (Geldreich and Kenner 1969, Geldreich 1976, Mara and Oragui 1981). This ratio in seals overlaps but is generally higher than the ratio reported for humans.

Fecal coliform contribution by harbor seals

Total fecal production of harbor seals in Quilcene Bay was estimated above at 57 to 115 kg per day and the geometric mean fecal coliform density in harbor seals was 3.1×10^7 fecal coliforms per gram. This would translate to 1.8 to 3.6×10^{12} fecal coliforms per day generated by the harbor seals that use Quilcene Bay. This figure represents the theoretical maximum contribution of harbor seals because it uses the maximum number of seals seen and and assumes all the feces generated by seals are being deposited in Quilcene Bay. Even though these feces are being deposited directly into the water only a proportion of the bacteria present are likely to become dissolved in the water column.

Conclusions

- Up to 230 harbor seals haul out on log booms and oyster rafts in Quilcene Bay.

- Calculated estimates of the fecal production of a typical harbor seal range between 250 and 500 grams per day.

- Geometric mean fecal coliform concentrations in 10 seal fecal samples was 3.1×10^7 per gram. This concentration is in the same range as for humans but is higher than most domestic animals.

- Data is insufficient to quantify seal contributions compared to other sources, however, these calculations indicate seals have the potential to be significant contributors to observed fecal coliform concentrations.

- Additional research is needed to more precisely calculate seal contributions including: expand the sample size on fecal coliform densities, determine portion dissolving in marine water, and examine other sites were seals congregate.

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"Chemicals and Biological Organisms in Puget Sound Recreational Shellfish"

J. Faigenblum*, G. Plews* and J. Armstrong#

Background

Research data collected in Puget Sound since the early 1980's showed the types and levels of chemical contaminants in the sediments, water-column and biota (Malins, 1980, 1982; Romberg, 1984). Some of the high chemical levels measured in the urban bays, and the discovery of fish with neoplasms and pre-neoplasms, sparked discussion about potential health risks to persons consuming seafood caught in urban bays. Concern was also expressed that recreational shellfish sites close to urban areas might be significantly affected by urban pollution.

In 1985, the EPA Region 10's Office of Puget Sound established an Implementation Committee, composed of federal, state and local agency representatives, members of industry, user groups and citizen advisory committees, to help the EPA with its formulation of a Puget Sound Estuary Program (PSEP). This committee identified a number of actions to be taken in support of the PSEP goals. One of the recommended actions was a study to measure levels of toxic chemicals and bacteriological indicator organisms in clams taken from recreational harvesting areas.

The EPA asked the Department of Social and Health Services (DSHS) to develop the study for funding. The resulting joint agreement was signed in 1986 between the DSHS and EPA, Region 10. The implementing agency was the Shellfish Protection Section (SPS), Office of Environmental Health Programs, DSHS, Olympia. The SPS's prime agency responsibility was to regulate the commercial shellfish producers and assure their compliance with sanitary standards set by the National Shellfish Sanitation Program (NSSP).

The overall study hypothesis was that sites closer to urban bays would show higher levels of contaminants and

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bacteriological indicator organisms than the reference site, a site well away from urban or industrial influences.

The chemicals were selected based on their toxicity, distribution and persistence in the environment. All of the chemicals were on the EPA's Priority Pollutant List and had been recognized as compounds of concern in Puget Sound (Tetra Tech, 1986).

The chemicals were:

a) Inorganic chemicals: arsenic (non-speciated), cadmium, copper, lead, mercury and zinc.

b) Organic chemicals: hexachlorobenzene (HCB), hexachlorobutadiene (HCBD), p,p'DDT, p,p'DDE, poly-chlorinated biphenyls (PCB's: as measured by Aroclor 1254) and polynuclear aromatic hydrocarbons (PAH's).

The biological indicator organism was the fecal coliform bacterium.

Shellfish sampling began in April, 1986 and was completed in August, 1987.

Choice of Target Species

The principal target species was *Protathaca staminea*, the native littleneck clam. The secondary target species was *Saxidomus giganteus*, the butter clam. These two species are the most harvested by the public.(Price and Ladd, 1978). Both clams are filter-feeders.

Sampling Sites

The location of the twenty sampling sites around Puget Sound are shown in Figure 1. The site codes used in Figure 1 are explained in Table 1. The reasons for choosing these specific twenty sampling sites included: a) being situated close to urban or industrial pollution sources; b) known heavy harvesting-use by the public and c) representation of different areas in Puget Sound.

Clams collected at quarterly intervals at these twenty sites were analyzed for fecal coliform levels. Clams taken from eight of these sites were analyzed for chemical concentrations. The chemistry sites are listed in Table 2. Alki Point, Dash Point, Mukilteo, Ross Point and Priest Point were expected to show signs of influence from nearby urban areas. One site, Birch Bay, in Whatcom County, was selected to be the reference site.

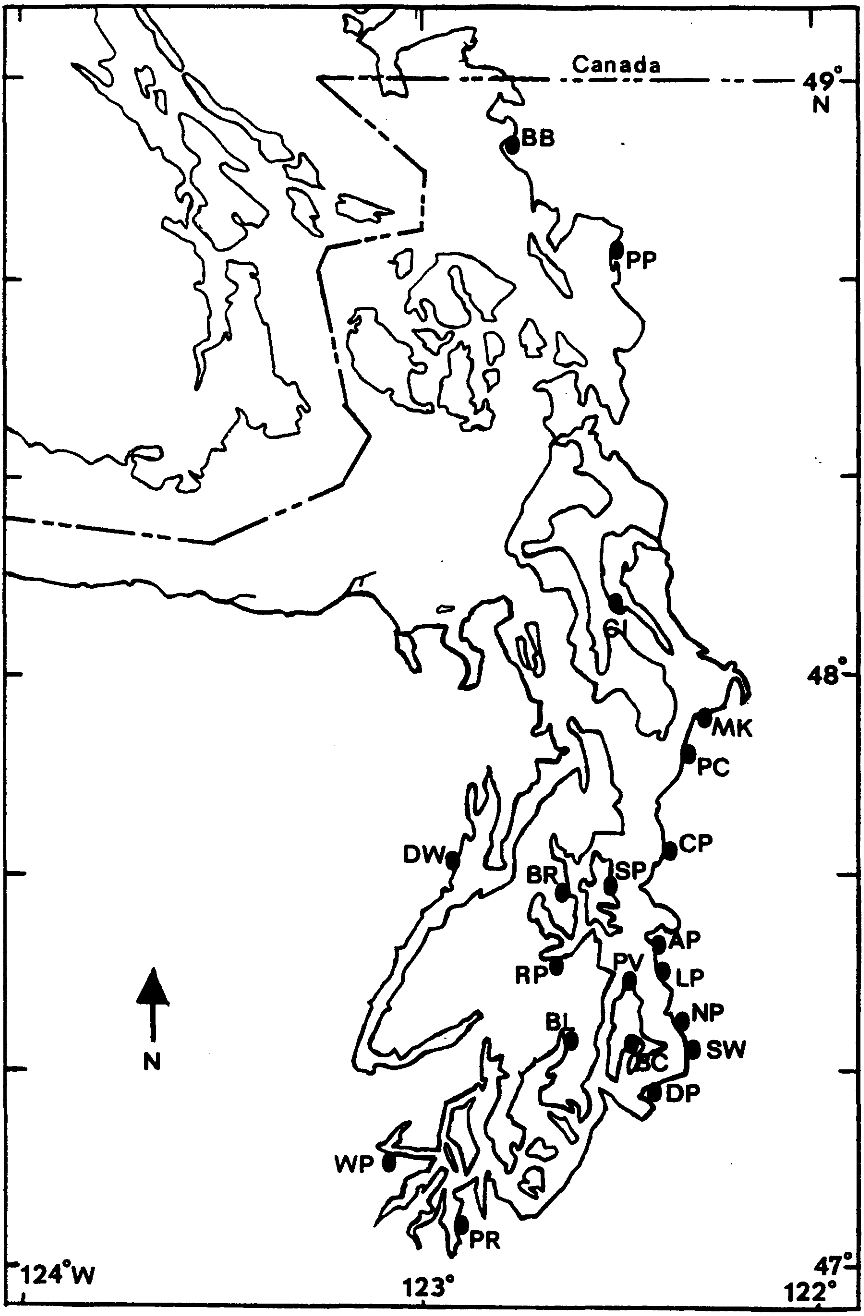

Figure 1: Map of Puget Sound with Sampling Sites

Sample Collection and Transport

The clams were dug from one or more locations along a 100 foot stretch of beach. Samples were collected during minus tides. The excavating tools used were clam-rakes or spades. The clams were retrieved by hand and placed

Table 1: DSHS-EPA Study Sites

Code	Site	County
AP	South Alki Point	King
BB	Birch Bay State Park	Whatcom
BC	Burton Acres County Park	King
BL	Burley Lagoon	Pierce
BR	Brownsville Marina	Kitsap
CI	Camano Island State Park	Island
CP	Carkeek Park	King
DP	Dash Point State Park	Pierce
DW	Dosewallips State Park	Jefferson
LP	Lincoln Park	King
MK	Mukilteo Fuel Tanks	Snohomish
NP	Normandy Beach Park	King
PC	Picnic Point State Park	Snohomish
PP	Post Point/S. Terminal Park	Whatcom
PR	Priest Point Park	Thurston
PV	Point Vashon	King
RP	Ross Point Tidelands	Kitsap
SP	Skiff Point	Kitsap
SW	Saltwater State Park	King
WP	Walker County Park	Mason

into a plastic bucket. Broken or cracked clams were discarded. There was no pre-collection preparation or cleansing of rakes, spades or buckets, it being assumed that their condition would not affect the protected tissues of the clam.

Table 2: Chemistry Sites

South Alki Point (West Seattle)
Birch Bay State Park (Whatcom County) [reference site]
Burton Acres County Park (Vashon Island)
Burley Lagoon (Pierce County)
Dash Point State Park (Tacoma)
Mukilteo Fuel Tanks (Mukilteo Ferry Dock)
Ross Point Tidelands (Bremerton/Sinclair Inlet)
Priest Point Park (Olympia/Budd Inlet)

Before leaving the beach, the clams were washed free of surface sediment, using seawater collected in the

bucket. Clams collected for inorganic, synthetic organic and pesticides analysis were transferred by hand to one-gallon borosilicate glass jars with Teflon lined lids, cleaned to EPA specifications. Clamss collected for bacteriologic analysis were transferred by hand to sterile plastic bags. The jar or plastic bag was then placed on ice and transported to the laboratory in Seattle. EPA Chain-of-Custody forms were used to keep track of all samples.

Sample Preparation and Digestion

Clams were shucked with sterile knives, with a new knife for each sample. Their shells were measured and the juices and all tissue material, including stomach contents, were blended and the resulting homogenate frozen at -10 degrees Centigrade prior to analysis.

Stomach and gut contents were included in the analysis since the health risk to humans consuming clams was the principal concern, and people consume all the tissue in the shell.

Inorganic Chemistry Analyses

Homogenate to be tested for arsenic, cadmium, copper, lead and zinc levels was digested using nitric and perchloric acids. Arsenic, cadmium and lead were analyzed using an Atomic Absorption Graphite Furnace Atomizer using the Jarrell Ash Video 11E with Smith Hieftje background correction. Copper and zinc were analyzed by Atomic Absorption Flame Atomizer using the Perkin-Elmer 306 AA. The homogenate to be tested for mercury was digested using sulfuric and nitric acids. Mercury was analyzed by the cold vapor atomic absorption method using the Coleman 50 Mercury Analyser. The inorganic analysis QA/QC procedures followed were reviewed and approved by the EPA's Regional QA/QC Officer.

The analytical procedure detection limits for the six heavy metals studied were:

Arsenic	0.2 ppm, wet weight;
Cadmium	0.01 ppm, wet weight;
Copper	0.6 ppm, wet weight;
Lead	0.04 ppm, wet weight;
Mercury	0.02 ppm, wet weight;
Zinc	5.0 ppm, wet weight.

Organic Chemistry Analyses

Organic chemicals in the shellfish tissue samples were analyzed by GC/ECD (for HCBD, HCB, p,p'DDT, p,p'DDE and

PCB's) and by HPLC/fluorescence (for PAH's). Extract confirmation by GC/MS was very limited, and applied to a few PAH extracts only. The detection methods used were not sufficiently specific to eliminate common interferences in the samples, at levels within the target analytical range. The QA/QC validation data set was not complete. A specific problem was the lack of matrix-recovery data for all analytes except for the PCB's. The data were less than fully validated or were obtained by less than definitive techniques.

As a result, the decision was made to consider the organic analysis data as screening-level data and make only limited use of it.

Microbiological Analyses

All shellfish tissue analyses for fecal coliform were done according to procedures specified in APHA standard methods (Greenburg and Hunt, 1984).

Inorganic Chemistry Results

A summary of the inorganic results are found in Table 3. The results presented are overall arithmetic averages by heavy metal and by target species. Asterisks indicate a statistically significant difference between the species means for a given chemical. The results are presented as ppm, wet weight.

The highest arsenic levels were found at Burton Acres County Park (Quartermaster Harbor). This supports the findings of others who have found elevated levels of arsenic and antimony in the Quartermaster Harbor area of Vashon Island (Crecelius, 1975). It is thought that the source for both metals was the ASARCO smelter near Tacoma and that the mode of transport was by air.

Arsenic values found in this study were found to agree with values published by other investigators working in Puget Sound and with values published for clams elsewhere in the country (Cummins, 1976; Romberg, 1984; Steimle, 1986).

The cadmium values found by the study were also found to be in agreement with values from research published from the Puget Sound and from other parts of the U.S. The clam, *P. staminea*, was observed to accumulate significantly more cadmium than *S. giganteus*.

A bentnose clam, *Macoma nasuta*, sample yielded a copper level greater than 30 ppm, wet weight, compared to the maximum *S. giganteus* level of 4.2 ppm. The copper values for the target species were in agreement with other

Table 3: Mean Levels of Heavy Metals in *P. staminea* and *S. giganteus*, Puget Sound, 1986-87

Results given in ppm, wet wt.

Metal	Species	N	Mean	S.D.	Range
Arsenic	*S. giganteus*	22	3.0	1.01	1.6 - 5.2
	P. staminea	32	2.7	0.78	1.3 - 4.1
Cadmium	*S. giganteus*	22	0.13*	0.071	0.04 - 0.39
	P. staminea	39	0.32*	0.097	0.10 - 0.54
Copper	*S. giganteus*	22	1.9*	1.11	<0.6 - 4.2
	P. staminea	32	1.3*	0.51	<0.6 - 2.4
Lead	*S. giganteus*	21	0.17*	0.115	<0.04 - 0.42
	P. staminea	25	0.08*	0.042	<0.04 - 0.18
Mercury	*S. giganteus*	19	0.02	0.005	<0.02 - 0.04
	P. staminea	25	0.02	0.004	<0.02 - 0.03
Zinc	*S. giganteus*	22	14.4	1.19	12.2 - 16.4
	P. staminea	39	15.2	2.03	11.7 - 21.2

* Statistically significant difference between species means, $p < 0.05$

Puget Sound values and other U.S. clam values. The butter clam was found to accumulate significantly more copper than the native littleneck.

The lead values for this study were found to be less than those found in other Puget Sound studies and less than those from other parts of the country. These discrepancies are most likely due to differences in analytical technique on the part of this study.

Mercury levels were found to be very low and close to the analytical detection limit of 0.02 ppm. The highest value, 0.04 ppm, was well below the 1.0 ppm FDA guideline for mercury in edible portions of fish and shellfish.

Zinc values were found to be in general agreement with other Puget Sound values and with values from around the U.S. Two *Macoma inquinata*, sand clam, samples yielded zinc values over 40 ppm, compared with the *P. staminea* maximum value of 21.2 ppm. Zinc values were noted to peak at all beaches in June, 1987.

The data suggested that bioaccumulation rates can differ by species. The local *Macoma spp.* tend to bioaccumulate copper and zinc to a greater extent than other Puget

Sound clam species. These are, however, two metals of lesser public health significance.

Results of statistical analysis of the inorganic chemistry data did not support the hypothesis that levels at other sites were less than levels at Birch Bay, the reference site. Birch Bay was the lowest site for both target species with lead. It was the lowest site for P. staminea with copper. For the other heavy metals, arsenic, cadmium, mercury and zinc, there were other sites with lower values than Birch Bay. The project's hypothesis could not be supported since it could not be shown that "urban" sites such as South Alki Point, Dash Point, Mukilteo, Ross Point and Priest Point had higher levels of contaminants than the "rural" sites.

Organic Chemistry Results

In keeping with the decision to treat the organic analytical results as screening level data, only the maximum values measured are reported in Table 4. The data in Table 4 have been suitably corrected for blank values and surrogate recovery efficiency measurements. The values reported in Tables 4 are interpreted to mean that actual values of a given compound in the samples were equal to or less than this maximum value of analyte plus interference. Results are given as ppb, wet weight.

Table 4: Organic Chemical Maximum Levels by Site
DSHS-EPA Recreational Shellfish Study,
Puget Sound, 1986-1987

Screening level values only
Results given as ppb, wet weight
Clam species: *P. staminea*, *S. giganteus*

Site	HCBD	HCB	DDT	DDE	PCB's *	PAH's
South Alki Pt.	ND	0.7	0.8	2.2	23	83
Birch Bay (Control)	ND	10.5	2.3	1.6	20	31
Burley Lagoon	ND	0.8	ND	0.8	23	33
Burton Acres Co. Pk.	0.1	0.9	ND	0.9	25	70
Dash Point St. Pk.	0.3	3.1	0.4	1.1	45	68
Mukilteo Fuel Tanks	ND	0.3	5.1	1.5	59	26
Priest Point Park	ND	0.3	3.1	1.2	51	81
Ross Point Tidelands	ND	0.4	0.7	1.4	35	92

ND = not detected
* Aroclor 1254 only

These maximum values were well below any current USFDA standards and were consistent with levels expected for non-urban, non-industrial sites.

Fecal coliform bacteria

Currently, there are no federal or state standards covering the acceptability or non-acceptability of recreational shellfish sites in Puget Sound. The classification of acceptability of a commercial shellfish growing-area is based on: 1) a detailed shoreline sanitary survey of the site to identify all possible sources of pollution; 2) an intensive water quality testing program of the water over the growing area, and of any other significant water sources entering the growing area; and 3) at least five shellfish meat samples taken within one month. No single type of information is judged to be adequate to judge the acceptability of a site, it requires all three types of information.

In this study, only the meat sample information was available. There was no accompanying water quality data or sanitary survey information. Therefore, it was not possible to judge the recreational sites by criteria used for commercial sites.

A 230 MPN fecal coliform shellfish meat level is used for commercial shellfish stock as a signal for further testing of the acceptability at the wholesale market level. Given the lack of water and sanitary survey data, an arbitrary decision was made to choose 230 MPN of fecal coliform in shellfish tissue to represent a limit of desirability when considering the recreational shellfish study data. It does not mean that this level represents a health risk to consumers of recreational shellfish.

Table 5 presents the fecal coliform results, by site, and by MPN value category. The MPN categories are: 1) less than 30; 2) between 31 and 230; and 3) greater than 230. Values less than 30 MPN indicate relatively clean samples.

Three sites had more than 70 percent of their samples below 30 MPN and had no samples with values greater than 230: Birch Bay State Park (reference site), Burton Acres County Park (Vashon Island) and Camano Island State Park.

Three sites had more than 70 percent of their samples greater than 230. These three sites, Point Vashon, Walker County Park and Dosewallips State Park, yielded samples that were by any standards polluted. Subsequent water samples taken at these three sites bolstered the finding that the sites have environmental quality problems. None of these sites were "urban".

Table 5: Percentage of Fecal Coliform Counts Falling into MPN Categories

Site	N	MPN Categories <30	31-230	>231
South Alki Point	6	17%	50%	33%
Birch Bay State Park	7	71	29	0
Burton County Park	7	86	14	0
Burley Lagoon	7	29	29	42
Brownsville	8	25	62	13
Camano Island State Park	7	71	29	0
Carkeek Park	5	20	60	20
Dash Point State Park	6	0	50	50
Dosewallips State Park	6	0	0	100
Lincoln Park	6	0	67	33
Mukilteo Fuel Tanks	7	14	57	29
Normandy Beach Park	7	29	57	14
Picnic Point County Park	7	14	43	43
Post Pt./S. Terminal Park	7	29	14	57
Priest Point Park	8	13	50	37
Point Vashon	7	14	14	72
Ross Point Tidelands	7	14	43	43
Skiff Point	7	57	14	29
Saltwater State Park	7	43	43	14
Walker Park	7	0%	0%	100%

The highest levels of fecal coliform in the study were found at a remote rural site, Dosewallips State Park (MPN value range: 790 - >24,000), contrary to all expectations. Water samples taken at the site confirmed the tissue results. A sanitary survey indicated several possible sources of pollution from septic tank drainage to seal feces. The Dosewallips findings do suggest that all sites have to be tested, and that lack of pollution cannot be taken for granted based on location.

Table 6: Percentage of Fecal Coliform Counts Falling into MPN Categories by Date of Collection

Sample Date	N	MPN Category <30	31-230	>231
June 1986	18	22%	50%	28%
October 1986	36	25	33	42
December 1986	20	60	25	15
April 1987	20	10	55	35
June 1987	20	25	30	45
October 1987	20	30%	30%	40%

The data was examined to see if there were changes in shellfish quality in different times of the year. Table 6 gives the data placed into three MPN categories by month of collection. Statistical testing showed that the December 1986 results were significantly different from both the October 1986 and April 1987 results, i.e. that there were more low-value MPN results in December 1986. It would take several other annual cycles of readings to verify this finding.

Conclusions

a) Inorganic chemicals:

More shellfish need to be analyzed for heavy metal levels to confirm the values found in this study. This study did not find levels of heavy metals concentration that should be of concern to public health authorities. Long-term health risk assessment is beyond the scope of this study. EPA, Region 10, has plans to use the data for long-term health risk evaluation.

b) Organic chemicals:

Levels of organic chemicals in recreational shellfish in Puget Sound need to be measured and confirmed. The screening level data resulting from this study suggests that none of the six organic compounds studied occur at levels that pose a short-term risk to public health.

c) Bacteriological indicator organisms:

Before regulatory action can be taken at a beach, three steps need to be taken: 1) measure levels of fecal coliform in the shellfish; 2) measure fecal coliform levels in the surrounding waters, to confirm levels measured in the shellfish; 3) a sanitary survey is completed to identify all sources of human and animal wastes and the potential for the presence of pathogens.

Under the 1987 Puget Sound Water Quality Authority's Management Plan, the Shellfish Protection Section is working with local health departments to develop criteria for regulatory limits at recreational shellfish sites. Also under consideration are procedures for public notification at beaches that exceed proposed recreational site regulatory limits.

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Uptake and Distribution of PSP Toxins in Butter Clams

Mark K. Beitler*

Introduction

Paralytic shellfish poisoning (PSP) can occur in man from the ingestion of bivalves which have fed on toxigenic *Protogonyaulax catenella* and *P. tamaresis*. Limited information is available on PSP toxin uptake, transport, retention, and loss in butter clam tissues. For many years it was believed that bivalves only concentrated PSP toxins from dinoflagellates ingested. However, recent findings suggest that some shellfish and bacteria associated with marine invertebrates can decrease and/or increase the lethality of the toxins by decarbamoylating them or transforming gonyautoxins (GTX) I-IV and neosaxitoxin (NEO) to saxitoxin (STX) (Sullivan *et al.*, 1983; Shimizu and Yoshioka, 1981; and Kotaki *et al.*, 1985).

This study was a continuation of previous research at the Institute for Food Science & Technology, U. of WA, to explore PSP toxin distributions in the marine food web. The projects were conducted from 4/85 to the present with support from the Washington Sea Grant Program. The purpose of the work described here was to test whether:
[1] nontoxic butter clams from the Hood Canal could absorb and retain PSP toxins from ingested *P. catenella* and form STX from other toxins,
[2] there are similarities between tissues which retain toxins in the feeding experiments and those of clams in the field, and
[3] there are trends in toxin type and concentration in different tissues of butter clams in the field.

Materials & Methods

Field studies

Butter clams were collected from Dockton County Park in Quartermaster Harbor off Vashon Island, Beckett Pt. in Discovery Bay, East Sound on Orcas Island, and Middle Ground in Sequim Bay.

Feeding studies

Nontoxic butter clams (N = 50) from the Hood Canal at Seabeck were put into 70L, filtered, aerated seawater maintained at 11 C

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and fed a total of 71L, clonal P. catenella for 2.25 days. Four clams were randomly sampled over 0-58 days after initiating the feeding and 8 tissues were dissected per clam and processed separately. The experiment was repeated except the shellfish were fed a total of 84L, clonal P. catenella for 8 days and 4-6 clams were randomly sampled over 0-83 days after starting the feeding. Pairs of 8 tissues were processed.

Tissue processing and PSP toxin analysis

Clams from Quartermaster Harbor and Discovery Bay were processed and analyzed by the method of Jonas-Davies and Liston (1985). Other shellfish tissues were homogenized in 0.10 N HOAc, filtered, and stored at -41 C until being analyzed for 8 PSP toxins, 2-5 times, by the high pressure liquid chromatography method of Sullivan and Wekell (1987).

Results

Feeding studies

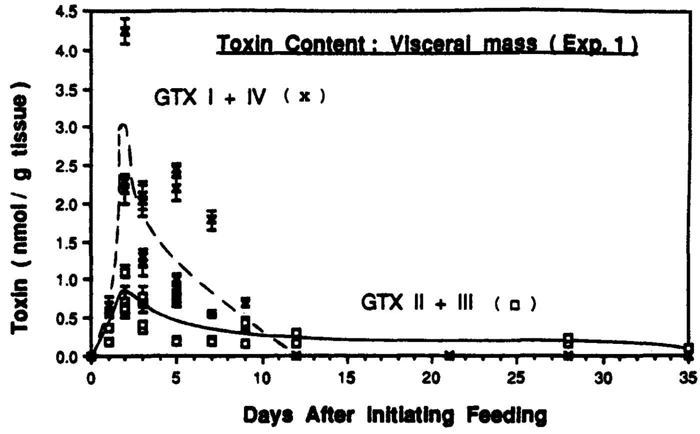
The P. catenella culture contained 19.8, 5.3, and 4.3 fmol/cell of GTX I + IV, GTX II + III, and NEO, respectively, and no detectable STX.

Butter clams from the Hood Canal absorbed and retained PSP toxins from ingested P. catenella (Fig. 1-2). All tissues were free of PSP toxins before the cultures were fed. GTX I-IV rapidly increased in the visceral masses in both studies during the feeding periods and gradually decreased after the feedings stopped. In the first experiment, 0.32-0.58 nmol GTX II + III/g tissue were detected in some of the kidneys on day 28 and persisted through day 58. Similarly, GTX I-IV increased in kidneys in the second study after the feeding stopped and were retained through day 83. In the mantle, pallial muscle, and remaining kidney in the second experiment, GTX I+IV was not detectable in these three tissues after day 27 but by day 83 low concentrations of GTX II + III were still present. In the gill of the second study, GTX II + III rose from days 0-27 but decreased to a low concentration by day 83.

Butter clams may form STX from GTX I-IV and/or NEO; STX was detected in siphons in both feeding studies and in the visceral mass, kidney, and in the mantle, pallial muscle, and remaining kidney of the second feeding study. STX persisted for more than 4 weeks in the siphons of experiments 1 and 2 and in the mantle, pallial muscle, and remaining kidney of the latter study.

Field studies

Not all butter clams sampled from bays in or near Puget Sound had high concentrations of PSP toxins (Table 1). Most of the shellfish collected at Quartermaster Harbor were free of toxins; only siphons sampled in 6/85 contained B1 and STX. In contrast, whole clams from Discovery Bay and Sequim Bay exceeded 80 µg STX equivalents/ 100g tissue, the legal limit for safe shellfish. These



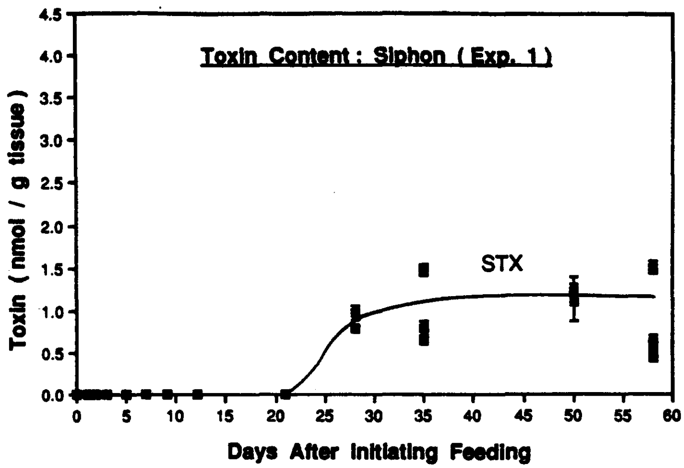


Fig. 1. Scatter plot of the PSP toxin composition of tissues of nontoxic butter clams (Saxidomus giganteus) fed P. catenella for 2.25 days. Each symbol represents the mean ± S.D. of 2-3 analyses of each tissue sampled.

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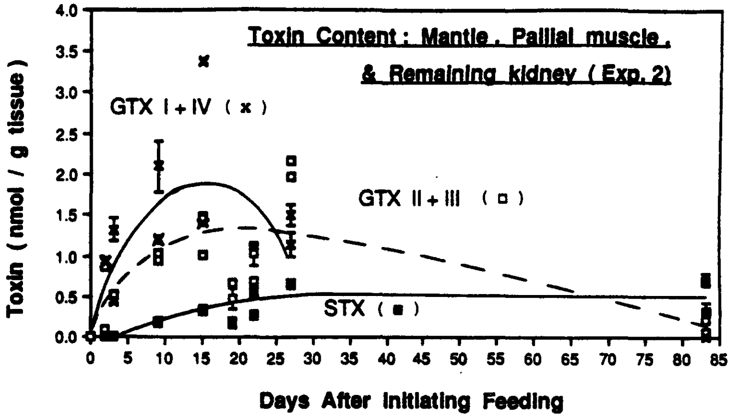
clams contained mainly STX and NEO and lower concentrations of B1 and GTX II + III.

The toxin distribution of experimentally fed clams matched that of shellfish in the field (Fig. 1-2, Table 2). Toxins were concentrated mainly in the siphon, kidney, mantle + remaining kidney and mantle + pallial muscle + remaining kidney. The highest total concentration of toxin was found in the kidneys of experimentally fed clams at day 83 and of shellfish collected at Orcas Island.

Fig. 2. continued



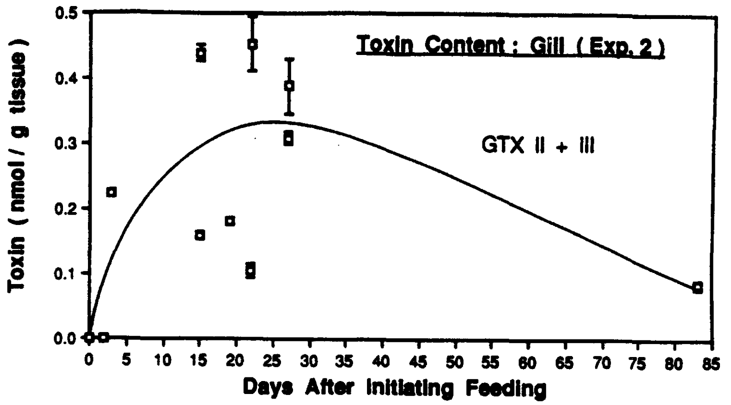


Fig. 2. Scatter plot of the PSP toxin composition of tissues of nontoxic butter clams (Saxidomus giganteus) fed P. catenella for 8 days. Each symbol represents the mean ± S.D. of 2-3 analyses of pairs of tissues collected.

STX was the major toxin in the tissues of clams from Sequim Bay and Orcas Island except where B1 and STX predominated in the kidneys (Table 2). In shellfish from Orcas Island, the kidney had the greatest toxin concentration but in the more lethal clams from Sequim Bay, the siphon, kidney, and mantle + remaining kidney contained the highest concentration of toxin. The kidneys of clams from both sites contained the largest number of different toxins.

Discussion

Results of the feeding studies suggest butter clams and/or bacteria associated with the shellfish may increase the lethality of GTX I-IV and/or NEO ingested by converting them to STX. It is unknown

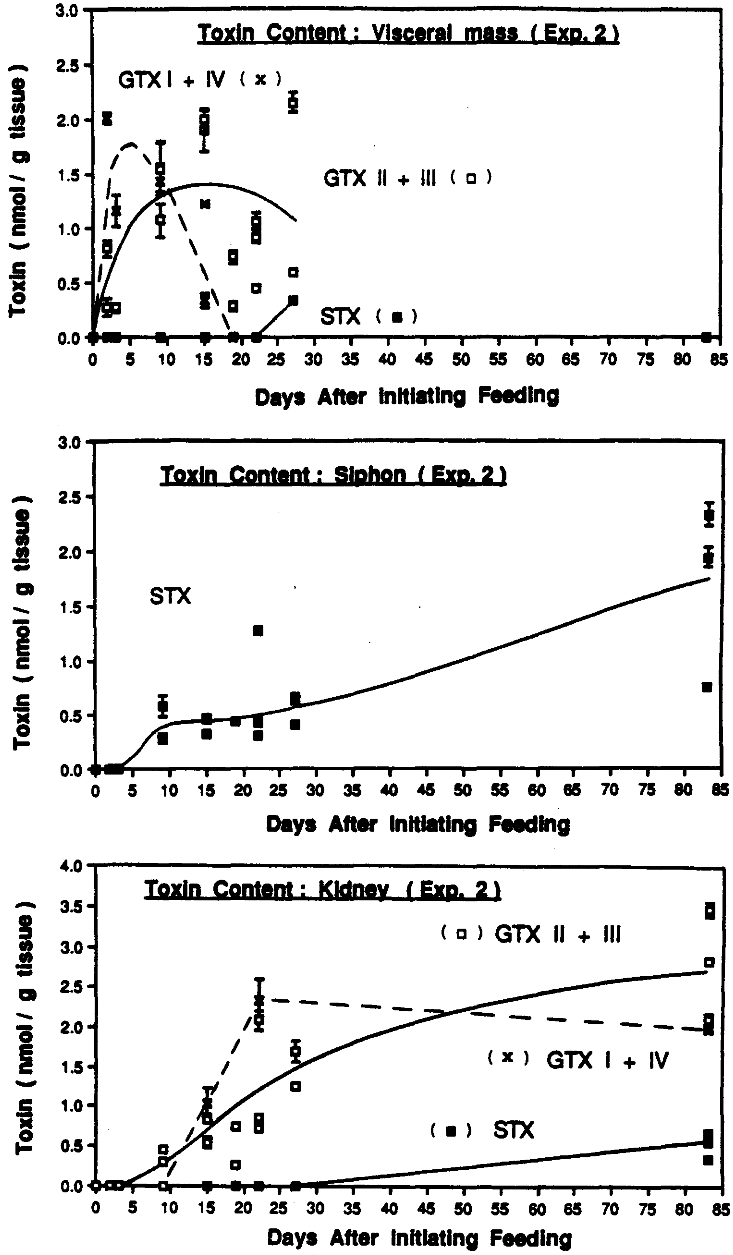


Fig. 2. Scatter plot of the PSP toxin composition of tissues of nontoxic butter clams (Saxidomus giganteus) fed P. catenella for 8 days. Each symbol represents the mean ± S.D. of 2-3 analyses of pairs of tissues collected.

Table 1. PSP toxin profiles of butter clams (Saxidomus giganteus) collected at Quartermaster Harbor, Discovery Bay, and Sequim Bay.

Collection Date	Description	N[a]	B1	GTX II + III	NEO	STX	Total
			nmol/g (µg STX equiv./100g)				
Quartermaster Harbor, Vashon Island							
4/ 8/85	Clams without siphons	2					0
6/20/85	" " "	5					0
	-siphons	5	2.47 (7)			2.67 (102)	5.14 (109)
7/ 7/85	Whole clams	3					0
7/17/85	" "	3					0
7/30/85	" "	2					0
	" "	2					0
8/28/85	" "	4					0
	" "	4					0
	" "	4					0
Beckett Pt., Discovery Bay							
9/14/85	Whole clams	2		0.36 (9)	1.43 (60)	1.69 (65)	3.48 (134)
Middle Ground, Sequim Bay							
8/25/87	Whole clams	32	0.98 (3)	0.33 (8)	2.35 (98)	7.5 (286)	11.2 (395)

[a] N = number of clams

what environmental factors might promote this transformation of toxins. Nontoxic butter clams from the Hood Canal have the potential for absorbing and retaining PSP toxins when exposed to P. catenella. If these shellfish ingested sufficient numbers of this alga, the clams could pose a threat to human safety.

There was no consistent pattern between the occurrence of PSP toxins in butter clams and geographic location. In Quartermaster Harbor, butter clams exceeded the legal limit for toxicity following small blooms of P. catenella in 1984 (Jonas-Davies and Liston, 1985) but the shellfish were below the limit the next year (Table 1). In contrast to Quartermaster Harbor, Discovery Bay and Sequim Bay contained hazardous clams. Because shellfish were collected from areas with low human populations and limited industrial growth, it is unknown what effects urban and industrial wastes may have had on P. catenella growth and, in turn, PSP toxin concentrations in butter clams.

Recommendations

Investigations are currently being conducted to determine whether the butter clam and/or its microflora are increasing the lethality of toxins ingested. Additional research should be performed to examine the role of bacteria and endogenous enzymes in shellfish in forming, interconverting, and destroying PSP toxins and the effects of changing environmental conditions on these reactions.

Table 2. PSP toxin distribution of butter clams (*Saxidomus giganteus*) from Sequim Bay and Orcas Island.

Middle Ground, Sequim Bay (68 clams collected, 8/25/87)

Tissue (36 clams)	% Total Toxin: GTX I + IV	GTX II + III	B1	NEO	STX	Total nmol toxin / g (Mean ± S.D.)
Mantle + remaining kidney	3	24		13	60	38.4 ± 18.2
Siphon			20	23	57	37.0 ± 11.7
Kidney	8	6	38	14	34	35.6 ± 4.9
Mantle		1	17	18	64	12.5 ± 5.2
Heart		1	15	21	63	12.3 ± 4.7
Pallial muscle		1	11	16	72	6.1 ± 1.6
Gill		4	2	33	61	4.6 ± 1.6
Mantle muscle			7	21	72	4.08 ± 1.53
Visceral mass		2	5	22	71	4.0 ± 2.3
Foot				45	55	1.16 ± 0.46
Blood				26	74	0.42 ± 0.26
Adductor muscle					100	0.36 ± 0.15
Whole body (32 clams)		3	9	21	67	11.2 ± 2.7

East Sound, Orcas Island (62 clams collected, 7/16/85)

Tissue	% Total Toxin: GTX I + IV	GTX II + III	B1	NEO[a]	STX	Total nmol toxin / g (Mean ± S.D.)
Kidney	4	10	46		40	13.46 ± 9.21
Siphon			45		55	4.33 ± 3.42
Visceral mass		1	5		94	2.60 ± 1.20
Gill		8			92	0.91 ± 3.20
Mantle muscle					100	0.24 ± 0.25
Adductor muscle						0
Foot						0

[a] Foreign material prevented the quantitation of NEO with any certainty.

Because nontoxic butter clams in the Hood Canal have the potential for becoming lethal, studying factors which affect the growth of *P. catenella* may help prevent this from occurring. Water from the Hood Canal should be tested to determine whether it inhibits the growth of this dinoflagellate vs. water from other areas of Puget Sound. If *P. catenella* will replicate in water from the Hood Canal, other factors which promote its growth should be explored. Experiments need to be conducted to determine what components of the natural environment and in urban and industrial wastes could induce blooms of this alga. Additional research will provide more insight into the development of PSP in clams and the growth of *P. catenella*. This information might help to prevent bivalves on the Hood Canal from becoming toxic and, in turn, slow the rising cost of monitoring shellfish for PSP in Washington.

Acknowledgements

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Summary Statement

Marleen M. Wekell*

This concludes the session on shellfish contamination. I thank the five speakers for their fine presentations.

Although we still do not have a complete understanding of all of the sources of contamination of Puget Sound shellfish, the information presented today gives us more insight on the issue. Contamination from human and naturally occurring sources can be found in shellfish harvested from certain areas of Puget Sound. The data of Kaysner et al. suggests that nonpoint sources such as from failing septic systems are contaminating shellfish from in shore areas of southern Puget Sound. Some of the bacteria isolated are potential human pathogens such as species of Salmonella, Hermonas, Vibrio and Yersinia. Inshore and deepwater environments of the Seahurst area are also contaminated with potential pathogens which show seasonal fluctuations (Matches et al.) with psychrotropic organisms such as Yersinia species found in greater numbers in the colder winter months.

In addition to human sources, harbor seals in Quilcene Bay and possibly in other areas have the potential of contributing indicator organisms (fecal coliforms) according to Calambokidis and McLaughlin. Although neither Salmonella nor Yersinia was isolated from a small sampling (10) of harbor seal feces, the health risks posed to humans consuming shellfish collected from areas frequented by marine mammals in Puget Sound are not understood.

Shellfish such as littleneck and butter clams from several areas of Puget Sound were found by Faigenblum et al. to contain varying levels of fecal coliforms as well as inorganic and organic contaminants. Sources of contamination were not always evident.

A final source of contamination of Puget Sound shellfish discussed today, Paralytic Shellfish Poison (PSP) occurs in some areas but not others. The work of Beitler indicates that butter clams from a traditionally non-toxic area (Hood Canal) have the ability to not only take up and retain PSP but they can change some of the algal PSP toxins into more toxic forms.

There are still more unknowns regarding contamination of Puget Sound shellfish. We know what some of the chemical and microbiological contaminants are and in some cases what levels are present. We do not

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always know how they got there or what factors influenced the process. In regard to PSP, we still do not understand what environmental parameters affect the growth and toxin production by the algae reponsible. It is not always clear how to prevent or reduce human sources of chemical and microbiological contamination of Puget Sound shellfish. In addition to human sources, it is not known what proportion of fecal contamination of shellfish is contributed by marine mammals or by birds and other animals.

Hopefully our continued research efforts in this field will help us answer these and other questions so that effective preventative measures can be employed.

DREDGED MATERIAL MANAGEMENT

HOW DO WE ASSESS AND AVOID ADVERSE EFFECTS ON LIVING RESOURCES?

Keith Phillips,
Washington Department of Ecology
Session Chair

Introductory Statement

Keith E. Phillips *

Decisions concerning the topic of dredged material management require significant government attention, and the topic is consequently too expansive to fully address in a single meeting session. There are at least two reasons for this. First, we may dredge over 300 million cubic yards each year in the United States just to maintain our existing navigation channels. And second, research into the environmental effects of dredging over the last 15 years has exceeded the $100 million mark.

On the other hand, dredging is less of an influence in Puget Sound. Volumes over the last 15 years have averaged around 1.5 million cubic yards per year. Nonetheless, with the current focus on contaminated sediments found in portions of our harbors and waterways, substantial attention has been recently devoted to dredging issues in the Sound. The federal and state Puget Sound Dredged Disposal Analysis (PSDDA) is developing a regional program for the unconfined, open-water disposal of relatively clean dredged material. Also, the occassional navigation development project can result in large volumes of material being dredged in a single year. Such is the case with the U. S. Navy Homeport project proposed for the Everett, Washington area.

As a comprehensive program, PSDDA is designating sites, establishing dredged material testing procedures and disposal guidelines, and defining site monitoring and management requirements. Several of the speakers today will refer to this program.

The focus of today's session is the interaction of dredging with living resources -- and how we assess and avoid those interactions. The speakers will provide some select insights into these questions, beginning at the dredging end. Can we predict the degree to which dredging will alter the availability of dissolved oxygen to aquatic life?

At the disposal site, what living resources are present and which should we avoid? How do we assess the value of various areas of the bottom to mobile fish and shellfish? After disposal, what happens to this value over time? And last, how do we make the necessary value judgments on which management decisions are based?

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Predicting Dredging Impacts on Dissolved Oxygen

John D. Lunz*, Mark W. LaSalle** and Leonard Houston***

Introduction

Haverstraw Bay is a greatly widened area of the Hudson River (5 km wide, 2.5-3.0 m deep shoals) some 35 mi (56 km) from its mouth at New York City. It is a known nursery area for several species of anadromous fishes, including striped bass, *Morone saxatilis*. Because of the bay area's recognized value to the fishery, the state resource agency (NY State Dept. of Environmental Conservation) expressed a concern for potential dredge-induced reduction in dissolved oxygen (DO) across the bay in late summer and fall when juvenile fishes congregate in the shoals. The U.S. Army Corps of Engineers (New York District and the Waterways Experiment Station) responded to the concern by constructing a simple, generally applicable numerical model to predict dredge-induced DO reduction.

The model was based on existing knowledge of suspended sediment concentrations around dredging operations, site-specific data on organic content of the sediment to be dredged, and river hydrology (flushing). The model was tested by monitoring DO levels during dredging operations in September and October 1987. Additional information on other sediment parameters which might be better predictors of DO reduction (i.e., ferrous iron, free sulfides) were collected and used in an alternative model. The original and alternative models were evaluated and compared using field monitoring results.

Methods

The model assumes that DO reduction is related to a) the oxygen demand (OD) of the sediment being dredged, b) the concentration of sediment suspended by the dredge, and c) the time period that a parcel of water (e.g., 1 liter) would be exposed to the suspended sediment field around the dredge. Oxygen demand was estimated by using existing data on OD and volatile solids (VS) concentrations reported for the Connecticut River (Issac, 1965) to generate a

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regression equation for predictive purposes. Volatile solids concentrations for Haverstraw Bay sedieents were estimated by analysis of total organic content (TOC) making the worst-case assumption that TOC = VS. Suspended sediment concentrations in the dredge plume were taken from a study of a bucket dredge operation reported by Bohlen et al. (1979). Residence time of a parcel of water within the suspended sediment plume around the dredge was calculated using data on flow rate and cross sectional area of the bay.

The predictive ability of the model was tested during dredging operations through daily monitoring of DO concentrations and optical turbidity levels during periods of lowest expected concentrations (sunrise and next slack tide). Measurements of DO and turbidity (surface, mid-depth, near-bottom) were taken at four equidistant stations around the dredge, located 300 ft (91 m) upstream, downstream, and to either side. Two additional stations were located 600 ft (183 m) and 1200 ft (366 m) downstream from the dredge. A control station was located outside the dredging area (near the upstream extent of the existing navigation channel).

Baseline data on DO and turbidity and the extent (if any) of impacts into the shoals were obtained by sampling three bay-wide transects across the entire width of the bay. Transects were located at both ends and near the middle of the channel being dredged. These transects were sampled weekly, beginning three weeks prior to dredging, and extended two weeks after dredging ended.

Additional data on ferrous iron and free sulfide concentrations were obtained for sediment samples collected from the dredged material barge and used to test an alternative model of DO reduction. This model is based on the assumption that these compounds are the most frequently encountered readily oxidizable material in estuarine and marine systems, and that they become fully oxidized upon suspension in the water column. Dissolved oxygen reduction is estimated by using stoichiometric equivalents for oxidative reaction of these materials at concentrations of suspended sediment observed around a bucket dredge (Bohlen et al., 1979).

Results

The average TOC value of Haverstraw Bay sediment samples was 15,886 mg/kg or 1.6% VS. Using the regression equation generated from data in Issac (1965), the estimated OD value for this VS concentration was 0.0115 mg DO/mg VS/4 days. Based on TOC values for the bay and suspended sediment concentrations of a worst-case dredging plume, 400, 200 and 100 mg/l at 100 (30 m), 1000 (305 m) and 1500 ft (457 m) from a dredge (Bohlen et al., 1979), estimates of VS concentrations and OD rates were calculated (0.0736, 0.0368 and 0.0184 mg DO/l/4 days at distances of 30, 305 and 457 m from the dredge, respectively). Proportioning the residence time within each subportion of a hypothetical suspended sediment field (30, 30-305,

305-457 m) over 4 days (a liberal estimate based on flow rate through the system) yielded an estimated DO reduction of less than 0.1 mg/l.

Daily DO monitoring was conducted from 10 September through 9 October 1987. For the purposes of this paper, data for the most frequently observed worst-case combination of time-of-day and tidal condition (sunrise/ebbing tide) are compared between stations around the dredge (Table 1). Stations are arranged in Table 1 in order of increasing theoretical effect of dredge-induced DO reduction (91 m downstream > 91 m lateral and upstream > 183 m downstream > 366 m downstream $\geq$ control).

Table 1. Mean deviation in dissolved oxygen concentration (mg/l), relative to control (overall range, 5.6-8.4 mg/l), at six locations around a bucket dredge during (n=4) and without dredging (n=16) and the difference between dredging and non-dredging. Values are for observations made at sunrise, under ebbing tide conditions.

Depth	Operational Status	91 m Down	91 m Lat.	91 m Lat.	91 m Up	183 m Down	366 m Down
Surface	Dredging	-0.08	-0.13	-0.03	-0.20	0.00	-0.13
	Non-dredging	-0.18	-0.16	-0.13	-0.10	-0.16	-0.15
	Difference	+0.10	+0.03	+0.10	-0.10	+0.16	+0.02
Mid-depth	Dredging	-0.10	-0.15	-0.10	-0.23	-0.05	-0.05
	Non-dredging	-0.20	-0.14	-0.04	-0.12	-0.11	-0.14
	Difference	+0.10	-0.01	-0.06	-0.11	+0.06	+0.09
Bottom	Dredging	-0.23	-0.13	-0.15	-0.15	-0.10	-0.08
	Non-dredging	-0.12*	-0.08	-0.02	-0.03*	-0.04	+0.01
	Difference	-0.11	-0.05	-0.13	-0.12	-0.06	-0.07

*n=15

Considerable variation in DO concentration, relative to the control station, was observed for non-dredging periods when the dredge was inoperative during sampling, but presumably operating up to several hours prior. These observations ranged from +0.7 to -0.9 mg/l for surface, +0.3 to -0.8 mg/l for mid-depth, and +0.3 to -0.6 mg/l for bottom measurements. Control station variability was often greater than that observed near the dredge.

Variation in DO observed when the dredge was operating during sampling ranged from +0.4 to -0.6 mg/l for surface, +0.2 to -0.5

mg/l for mid-depth and +0.2 to -0.6 mg/l for bottom measurements. Overall, dredging had a positive effect on surface DO concentrations, a positive or slightly negative effect on mid-depth DO concentrations and a slightly negative effect on bottom DO concentrations around the dredge. The stations most affected by the dredge appeared to be the 91 m upstream and downstream stations. Maximum deviations in DO concentration, however, were generally less than 0.20 mg/l. Associated data on turbidity in the vicinity of the dredge showed levels generally at or below 10 NTU's (equivalent in this system to about 40 mg/l) in the surface and mid-depth levels to as high as 40 NTU's (equivalent to about 160 mg/l) in bottom waters. Suspended sediment levels were thus less than half those used for the model predictions.

Baseline monitoring of DO prior to dredging showed variation in DO concentrations, measured in the channel proper, ranging from 0.1 to 0.7 mg/l for surface, 0.1 to 0.7 mg/l for mid-depth, and 0.2 to 0.9 mg/l for bottom measurements.

Measured concentrations of ferrous iron and free sulfides ranged from 176.0 to 483.1 ng/mg and from 1023.1 to 2621.6 ng/mg sediment, respectively. Applying the stoichiometric equivalents of 2.327 mg Fe/mg DO and 0.501 mg S/mg DO to values from 11 sediment samples yielded a mean total DO reduction of 0.317 mg/l at 100 mg/l suspended sediment concentration. DO reduction at 200 and 500 mg/l suspended sediment concentrations were calculated to be 0.634 and 1.585 mg/l, respectively.

Discussion

Judging from the results of this monitoring study, the TOC based model of DO reduction underestimated DO reduction while the alternative model, based on concentrations of oxidizable iron and sulfides, more closely predicted DO reduction around a bucket dredge operation. The difference in predictive accuracy between the two approaches is due to the inherent temporal differences in the oxidation rates of the predictive agents. For TOC, the model is based on the relationship between volatile solids concentrations and oxygen demand which acts over the course of days. This reduction in DO concentration is mediated by biological activity (BOD) acting on the volatile solids within the sediment. Iron and sulfides react very rapidly (within seconds or minutes) creating an immediate oxygen demand. This second scenario better fits the actual conditions surrounding an operating dredge where anoxic sediments remain in suspension for only a short period of time. The reason that predicted DO values were greater than observed may be because the suspended sediment concentrations observed in the field studies were significantly less than the value used as a model parameter (160 mg/l versus 400 mg/l). Mixing, not accounted for in this simple model, may also have reduced observed DO values below predicted levels. The predicted values, would have thus overestimated DO by a factor of two.

Results of the monitoring study suggest that DO reduction induced by an operating bucket dredge is minimal: generally less than 0.1 mg/l with maximum reduction of no more than 0.2 mg/l. It is important to point out, however, that natural variation in DO concentration, as measured in the three pre-dredging weekly transects, was, on some occasions, greater than that observed near the dredge. Dissolved oxygen concentrations were also observed to be somewhat more variable on non-dredging days, suggesting that an extrinsic factor(s) may be affecting DO.

Comparative information on dredge-induced reduction in DO is limited to two studies: a bucket dredging project in a highly industrialized channel in New York (Brown and Clark, 1968) and a hopper dredging project in a tidal slough in Oregon (U.S. Army Engineers, 1982). Oxygen depletion in the New York channel ranged from 16 to 83 percent (ambient range, 4.5-8.2 mg/l) in the mid to upper water column and up to 100 percent in near-bottom layers during December and March dredging activity. Conditions in the channel were complicated by reduced tidal flushing. Dredge-induced DO reduction (1.5-3.5 mg/l) at the Oregon site was limited to slack water conditions in the bottom 1/3 of the water column persisting until tidal flow resumed (within 2 hrs). Dissolved oxygen concentrations were observed to actually increase (by 2.0 mg/l) under flood tide conditions. In the present study, DO concentrations during slack water and flood tide conditions were generally similar to that shown for ebb tide conditions (Table 1).

Recommendations

Based on the results of this study, the alternative model of DO reduction, using sediment concentrations of readily oxidizable compounds (i.e., ferrous iron, free sulfides), appears to be a better predictor of DO reduction around dredging activities. While predicted DO depletion was slightly greater than that actually observed, the model served to provide a liberal estimate of DO reduction which is preferable, particularly in light of the highly variable conditions which can exist in estuarine systems. The presence of considerable natural DO variation stresses the importance of good pre-dredging baseline data for putting any dredging monitoring data into true perspective.

Acknowledgments

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Invertebrate Resource Assessments in and around Proposed Dredged Materials Disposal Sites in Puget Sound*

Paul A. Dinnel, David A. Armstrong, and Robert R. Lauth

Introduction

The multi-agency Puget Sound Dredge Disposal Analysis (PSDDA) Program was formed to site, evaluate, and manage the long-term, unconfined, disposal of dredged sediments in Puget Sound. As part of the siting process, trawl assessments of demersal invertebrate and bottomfish resources (See Donnelly et al. this conference, for a summary of the fish studies) were conducted in and around 15 proposed disposal sites in 10 general areas of Puget Sound for the purpose of siting disposal areas to minimize potential resource conflicts.

Coincident with the PSDDA evaluations was the need of the U.S. Navy to identify a confined (capped) disposal site in Port Gardner for open-water disposal of contaminated sediments from the Navy Homeport site at Everett, WA. With the support from these two separate projects, seasonal trawl assessments were made at PSDDA Phase I sites (Central Puget Sound, including the Navy site at Port Gardner) in 1986 and at PSDDA Phase II sites (North and South Puget Sound in addition to a second year assessment in Port Gardner) in 1987.

The object of this paper is to provide a synopsis of the methods and sites involved in the trawl study and provide a summary of the general findings together with appropriate references to the detailed final reports.

Methods

The areas sampled during 1986 and 1987 are shown in Fig. 1. Phase I (1986) sampling included two proposed sites each in Elliott and Commencement Bays, three sites in Port Gardner and one site in Saratoga Passage. Phase II (1987) sampling was conducted around two sites each in the Nisqually area and Bellingham Bay and one site each in the Strait of Georgia, Rosario Strait, and

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PSDDA SAMPLING AREAS

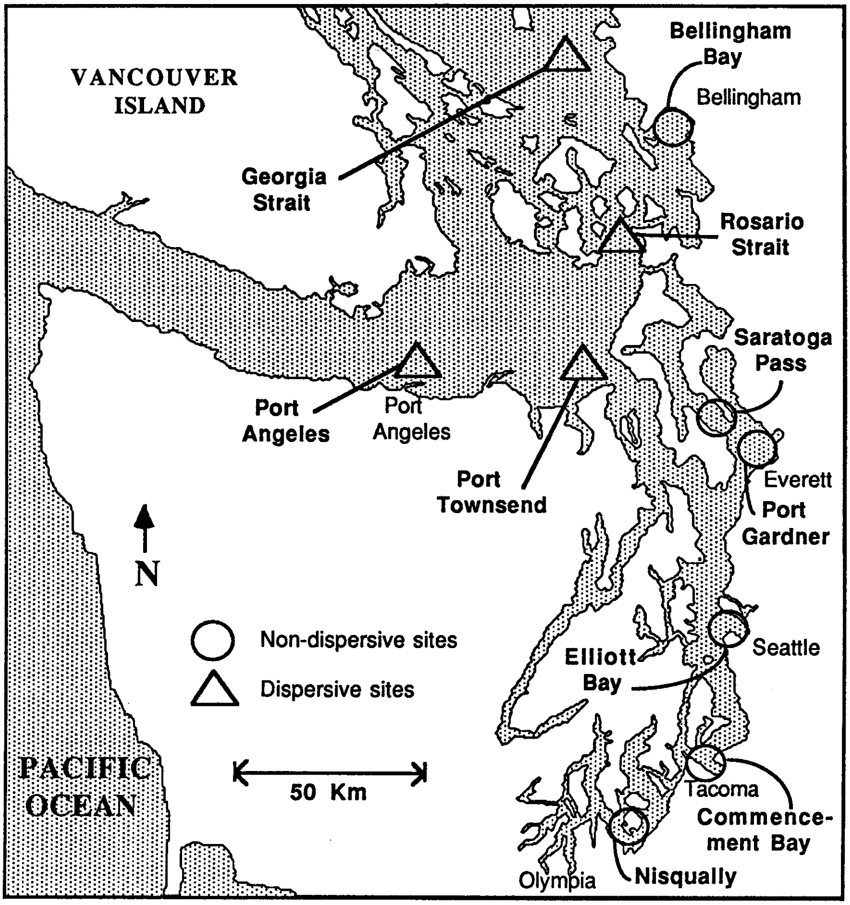

Figure 1. Map of Puget Sound showing the PSDDA sampling locations.

near Port Townsend and Port Angeles in the Strait of Juan de Fuca. The latter four sites were "dispersive" in nature and received less sampling effort than the other sites which were considered "non-dispersive".

Generally, each area was sampled on a seasonal basis except for the dispersive sites (April and October only). Sampling consisted of single tows of a 3-m beam trawl (Gunderson and Ellis 1986) pulled by the 16-m research vessel Kittiwake for about 5 minutes at a target ground speed of 2.5 km/hr. Each tow was gauged by radar ranges to be 1/8 nautical mile (about 232 m) long which produced an estimated area swept by the net (opening = 2.3 m) of about 530 m^2. The number of stations sampled in each area varied from 14 (Saratoga Passage) to 95 (Port Gardner) for the non-dispersive sites and from 6 to 11 for the dispersive sites. A portion of the stations sampled were within the boundaries of the prospective disposal sites and the remaining stations stratified by depth around the sites.

All Cancer spp. and Chionoecetes spp. (tanner) crabs caught in the trawl were counted, sexed, and assessed for molt and reproductive condition. Pandalid shrimp were identified to species, counted, measured and checked for eggs. Other invertebrates of actual or potential resource concern (e.g., scallops, mussels, sea urchins, sea cucumbers, etc.) were enumerated but not measured.

Further details of the sampling methods, sites and stations are recorded in the project final reports (Dinnel et al. 1986, 1988a, 1988b) submitted by the University of Washington.

Results

Non-dispersive sites

Nisqually. Trawls in and around two Zones of Siting Feasibility (ZSFs) showed that invertebrate resources were minimal in both zones. The major resource of concern in this area is the sea cucumber, Parastichopus californicus, which was most common at depths shallower than the proposed disposal sites. A small population of Dungeness crab, Cancer magister (probably survivors of one successful year class), was found, but none were caught within the ZSFs.

Commencement and Elliott Bays. Invertebrate resources of concern were scarce in and around the ZSFs in these two urban embayments. A few Dungeness crab were caught in Elliott Bay and several species of pandalid shrimp

were present in both areas, but not at densities presently considered to be of commercial importance.

Port Gardner. A substantial population of Dungeness crab (up to about 200,000 adults, mostly females) was found to reside in Port Gardner year-round, and portions of this bay are important for egg-bearing (gravid or ovigerous) females. This discovery was responsible for the relocation of the Navy's Homeport confined disposal site (for contaminated sediments) from an inshore location at 80 m depth to a site less frequented by crab between 90-130 m depth. This finding was also partially responsible for the eventual choice of a PSDDA unconfined disposal site in the deeper, offshore area of Port Gardner where crabs are relatively rare. In both cases, the choices of deeper sites in Port Gardner should also minimize potential impacts to shrimp and bottomfish (Donnelly et al., this conference) resources.

Saratoga Passage. Invertebrate resources were minimal (mainly a few pandalid shrimp) within the Saratoga Passage ZSF but Dungeness crab and sea cucumbers did occur in the shallower areas. Present plans do not call for a disposal site in Saratoga Passage due to the selection of one of the two Port Gardner sites.

Bellingham Bay. Bellingham Bay was relatively rich in invertebrate resources, especially Dungeness crab, pandalid shrimp, and the large nudibranch, Tritonia diomedea, which is valuable for neurophysiological research because of its large nerve fibers. While the PSDDA siting process relies on the trawl data to help select a final site location in Bellingham Bay, the question of whether or not a site is finally acceptable in terms of resource considerations by the various management agencies and the public may be a bigger question for this embayment. Presently, there are few criteria or standards for objective resolution of development/resource conflicts of this nature, although several are under consideration (see Clarke, this conference).

Dispersive sites

As previously mentioned, resource assessment at the dispersive sites was less rigorous (two seasons only at 6-11 stations) compared to the non-dispersive sites. The reasons for this were two-fold: 1) the concept of PSDDA adopting a dispersive philosophy was tentative and, 2) demersal resources should suffer less impacts in a dispersive site due to maximized dilution and dispersion of disposed sediments. General results of trawl surveys at the dispersive sites were as follows:

Strait of Georgia. Resources were scarce within this deep-water (~200 m) ZSF and limited to an occasional shrimp or scallop (including the rare weather-vane scallop, Pecten caurinus). Dungeness crab were caught in fair numbers inshore of the ZSF, but were limited to depths less than about 100 m. Catches of sea urchins (Strongylocentrotus pallidus and S. droebachiensis) and mussels (Modiolus) in the southern portion of the ZSF indicated a hard, rocky bottom, while large catches of brittle stars in the northern portion indicated a sandy bottom.

Rosario Strait. The Rosario Strait site is very rocky and highly affected by tidal currents. This area, which was sampled entirely by rock dredge, was dominated by pink scallops (Chlamys spp.) sea urchins, and mussels. No Cancer crabs (except small C. oregonensis) and only a few small pandalid shrimp were caught.

Port Townsend, Strait of Juan de Fuca. This site was dominated by pink scallops, small pink (Pandalus borealis) or coonstripe (P. danae) shrimp, and sea urchins.

Port Angeles, Strait of Juan de Fuca. The invertebrate catches at this site were very similar to the Port Townsend catches except that coonstripe shrimp were absent and a few sidestripe shrimp (Pandalopsis dispar) were caught.

Discussion

The trawl surveys conducted as part of the PSDDA (Dinnel et al. 1986, 1988a) and Navy Homeport (Dinnel et al. 1988b) projects provided basic biological resource data which aided final siting of five dredged materials disposal sites in Puget Sound, and identified potential resource conflicts which may affect the eventual establishment of a disposal site in Bellingham Bay. In some cases the data favored areas tentatively selected based on other siting factors (e.g., currents, depth, navigation lanes, cost, etc.), while in other cases (e.g., the Navy and PSDDA sites in Port Gardner) the final siting decisions were very dependent on resource considerations. Siting decisions based, in part, on seasonal resource densities should help to minimize adverse short-term impacts due to physical site disruption as well as long-term impacts due to elevated toxicant concentrations in disposed sediments.

In addition to the use of the trawl data for siting purposes, "baseline" information is also provided for

evaluation of future disposal activities at these sites. Presently, little quantitative invertebrate resource data exist for Puget Sound. Past work includes only an early shrimp assessment (Smith 1937) using a commercial-sized otter trawl and some seasonal beam trawl sampling by English (1976) in four general areas (Port Gardner, March Point, East Sound and Cherry Point) as part of an oil baseline study. Thus, the work discussed in this paper represents the most current and comprehensive invertebrate resource survey undertaken to date. Besides providing siting information, these surveys have provided additional insights into recruitment times, growth, periods of molting and egg production for crustacean species, and identification of some favored habitats. In the case of the two-year data base in Port Gardner, valuable measures of interannual variability have been obtained.

Presently, the Puget Sound Water Quality Authority is addressing the need for a long-term, comprehensive program to monitor Puget Sound and its resources (PSWQA 1987). This program will develop and implement a monitoring plan which will evaluate long-term trends in the health of Puget Sound and its resources. Of prime importance in any long-term plan is the ability to build on the present data base and maintain a consistency in sampling methodology and stations. The time is ripe to build on the Sound-wide PSDDA/Navy sampling program which has been carried out in the last two years and has involved some 1,500+ trawl samples throughout the Sound.

Acknowledgements

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Demersal Fish Assemblages Sampled at Puget Sound PSDDA Sites[1]

Robert F. Donnelly, Shelley C. Clarke, Robert R. Lauth, Bruce S. Miller and John H. Stadler

Introduction

Several communities bordering Puget Sound are home to industrial and recreational facilities that require access to nearshore and estuarine waters. These facilities (both existing and planned) are usually in areas that are periodically dredged to maintain water depth for vessel use. The Puget Sound Dredge Disposal Analysis (PSDDA) group was formed to identify and evaluate aquatic sites where dredged materials could be disposed of and managed in Puget Sound. The PSDDA group was composed of members from agencies involved with management and resource issues in Puget Sound. Final site selection was partially based on evaluation of the biological resources found at each of the proposed disposal sites.

This paper gives a general overview of the trawl studies conducted by the University of Washington to assess bottom fish resources at, and adjacent to, each proposed disposal site, and implications for long term monitoring.

Materials and Methods

Six areas designated for the permanent (non-dispersive) storage of dredged materials were sampled in and around the following areas (Fig. 1): the Nisqually region, Commencement Bay, Elliott Bay, Saratoga Passage, Port Gardner and Bellingham Bay. Primary and alternate sites were located in each area except Saratoga Passage, which had only one site. One of the Port Gardner sites was later proposed as the location for confined disposal of dredged materials from the U.S. Navy Homeport construction. Four additional sites were selected for disposal of relatively uncontaminated dredged materials: two were in the Strait of Juan de Fuca (one each near Port Townsend and Port Angeles), one in Rosario Strait and one in the Strait of Georgia (Fig. 1). These sites were labeled

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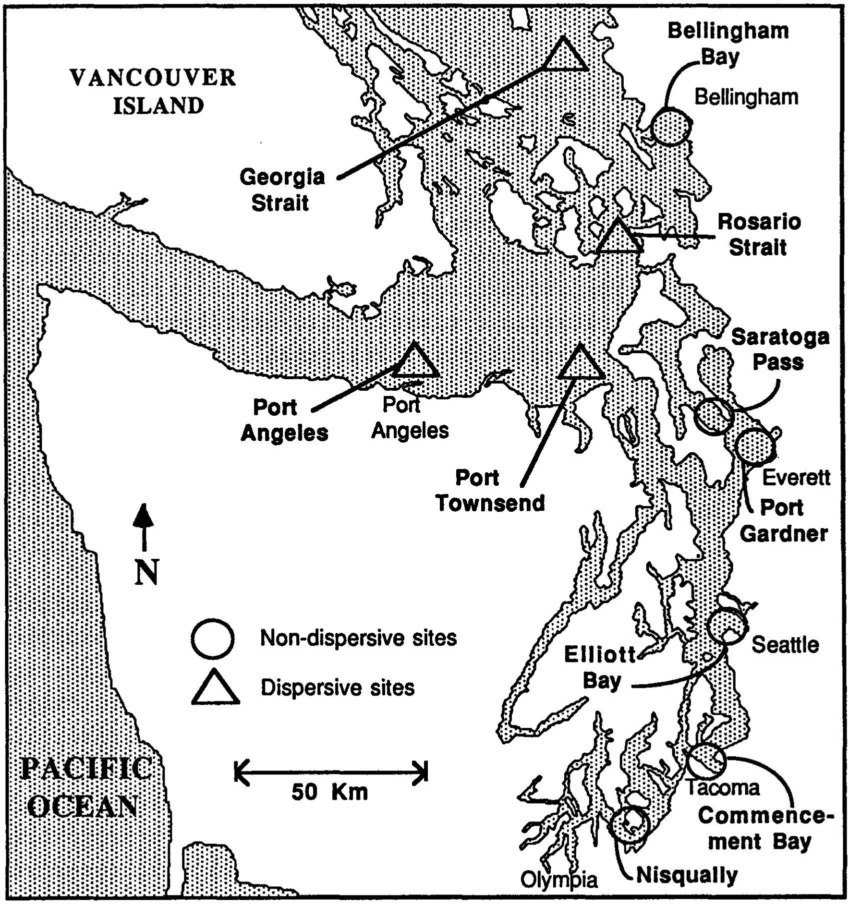

Figure 1. Map of Puget Sound showing the PSDDA sampling locations.

"dispersive" because dredged materials would be dispersed by the strong tidal currents in each area. Since dispersive sites were not intended for permanent storage, they were only sampled twice.

The number of times each area was sampled ranged from one in Saratoga Passage to five in Port Gardner. Multiple samplings were done by season. Sampling adjacent to each proposed disposal site was stratified according to depth with several collections taken at each depth or stratum. The stations sampled for fish resources consisted of a subset of the stations sampled for invertebrate resources (see Dinnel et al., this conference). The sampling gear

consisted of a 7.6 m, semi-balloon, two panel otter trawl (Mearns and Allen 1978) and a rock dredge. The otter trawl was towed from the research vessel Kittiwake at a target ground speed of 4.2 km/hr for a distance of 370 m. All fish resource stations were sampled with the otter trawl except for those in Rosario Strait where the rough bottom required the use of a rock dredge. The samples were sorted to species and enumerated in the field, then placed in plastic bags, marked, put on ice and later frozen. In the laboratory, lengths, weights and life history stages were recorded. For greater detail on sampling materials, methods and analyses see the project reports by Donnelly et al. (1986, 1988) and Lauth et al. (1988).

Results

Non-dispersive sites

Nisqually region. The two proposed sites or Zones of Siting Feasibility (ZSFs) were located at different depths and had different fish assemblages. ZSF 3, the western site, was dominated by subadult English sole (*Parophrys vetulus*) throughout the year. Shiner perch (*Cymatogaster aggregata*) and other small fishes, especially blackbelly eelpouts (*Lycodopsis pacifica*), were seen during winter and spring. The eastern site was almost twice as deep (≈120 m) as the western site and was characterized by the presence of English sole and Dover sole adults (*Microstomus pacificus*), ratfish (*Hydrolagus colliei*) and the occasional quillback rockfish (*Sebastes maliger*). The species assemblages changed with depth and season at all sampling stations.

Commencement and Elliott bays. The ZSFs within these two bays were only sampled twice, summer and autumn. The Commencement Bay ZSFs contained the least fish of all the sites designated for the permanent storage of dredged materials. In contrast, the Elliott Bay ZSFs had high numbers of fish and many species. Both bays showed differences in fish assemblages based on depth. Generally, the deeper the sampling site, the fewer the species.

Port Gardner. On the basis of depth and time, differences in species assemblages were seen in this bay. The make-up of the fish assemblages changed from season to season for depths to 80 m. These shallow strata generally had higher numbers of species and individuals and more complex assemblages than fish assemblages at the deeper strata (>80 m). Below 80 m, five species dominated: English sole, Pacific hake (*Merluccius productus*), Dover sole, slender sole (*Lyopsetta exilis*) and ratfish. Some of these species underwent apparent migrations during the sampling period. Pacific hake showed signs of movement into and out of the area while English sole appeared to move vertically.

Saratoga Passage. Saratoga Passage was sampled only once and the fish assemblages varied with depth. The number of species and number of individuals decreased with increasing depth.

Bellingham Bay. The catches of fish in Bellingham Bay were similar at most of the stations. Bellingham Bay is shallow and flat with a bottom depth of about 25 to 30 m. Small individuals of several species, primarily longfin smelt (*Spirinchus thaleichthys*) and English sole, were often collected in high numbers. The variety of flatfish was greater in Bellingham Bay than any other area sampled, English sole, flathead sole (*Hippoglossoides elassodon*), butter sole (*Isopsetta isolepis*) and starry flounder (*Platichthys stellatus*) all being found in abundance. The fish assemblages at the few shallow stations differed from those found on the flat bottom, and at all locations varied with season and depth.

Dispersive sites

Few species and few individuals were caught at the Port Angeles ZSF, except for walleye pollock (*Theragra chalcogramma*) during the October sampling. The walleye pollock were primarily subadults. Very few individuals or species were captured at the Port Townsend ZSF, with walleye pollock dominating the catches in October. Rock dredge sampling at Rosario Strait resulted in the capture of few species and individuals. The catches, even though small, contained several species of snailfish (*Liparis* spp.). Small numbers of fish were captured in the Strait of Georgia ZSF. However, at stations adjacent to the ZSF, catches were larger and showed an inverse relationship with depth.

Discussion

The PSDDA bottomfish studies provided useful data on the fish resources present in the ZSFs. These data were used by PSDDA in their final site selections. In addition, these studies generated valuable information on fish assemblages that can be used as baseline data for post-disposal monitoring.

The results of the PSDDA studies indicated that the fish assemblages were dynamic through space and time. Species assemblages at given depths varied seasonally. The fact that assemblages in Puget Sound varied regionally is possibly due to the distinct physical characteristics of each area. Some species underwent annual vertical migrations, others appeared to move into and out of study areas and some species appeared to be non-migratory. Results from this and other studies (Donnelly et al. 1984a, 1984b), indicate that Puget Sound bottomfish assemblages

are dynamic, changing from season to season, while showing similar processes from year to year.

The Puget Sound Water Quality Authority (PSWQA) is planning to establish a long-term program to monitor biological resources in Puget Sound (PSWQA 1987) and one objective of the program will be to monitor changes in these resources. The PSDDA fish data provides a potential baseline of information for long-term monitoring. Further, work is presently underway to assemble all the historical data on demersal fish in Puget Sound (see Miller and Moulton, this conference). Monitoring bottomfish assemblages would be preferable to monitoring a few individual species since assemblages would be better indicators of change in the environment (Warren 1971). In addition, bottomfish resource surveys should consider fish dynamics to best evaluate fish assemblages.

Consistent data collection is also an important aspect of long-term monitoring because changes in fish assemblages will be indicative of changes (positive or negative) in the environment. All fishing gear is selective and any changes in methods (e.g., velocity) or gear will change the portion of the fish assemblage that is sampled. Therefore, adopting the sampling gear and methods already employed in the PSDDA studies (and previous Puget Sound fish studies) would allow the incorporation of those data into any monitoring program.

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EVALUATION OF BENTHIC HABITAT QUALITY AND BOTTOMFISH FEEDING HABITAT POTENTIAL AT PSDDA DISPOSAL SITES IN PUGET SOUND

David R. Kendall* and Douglas Clarke**

Introduction

Dredging and disposal projects in Puget Sound embayments may have profound impacts on benthic habitat quality at both dredging and disposal sites. Environmental monitoring programs of dredging and disposal operations have traditionally focused upon detection of changes in benthic communities. In addition to their utility as indicators of changed benthic quality, benthic organisms have been perceived as appropriate targets of monitoring attention due to their importance as a forage base for valuable fisheries resources. Knowledge of the consequences of altered benthic conditions on trophic pathways to date have, however, been speculative. Insight into impacts to benthic-pelagic trophic linkages would provide the dredged material manager with more meaningful information than conventionally collected lists of faunal abundances (Rhoads et al., 1978; Lunz and Kendall, 1982; Becker, 1984; Rhoads and Germano, 1986; Becker and Chew, 1986). Site selection studies at Puget Sound Dredged Disposal Analysis (PSDDA) non-dispersive sites provided an opportunity to apply this approach (Clarke, 1986; Clarke and Kendall, 1988). The objectives of this paper are (1) to describe a comparative evaluation of benthic community and fish food habits data sets from the PSDDA Phase II North and South Puget Sound study areas with the intent of estimating functional as well as structural aspects of benthic conditions, and (2) to illustrate the application of trophic support information in dredged material management decisions.

Methods

Two non-dispersive Zones of Siting Feasibility (ZSF) were located near the Nisqually delta between Anderson Island and Devils Head (Devils Head ZSF) and Anderson Island and Ketron Island (Ketron Island ZSF). Two additional ZSF's were located in northern and southern Bellingham Bay. During July 1987, 22 box core stations were occupied within the Devils Head and Ketron Island ZSF's, and 17 stations were occupied in the Bellingham Bay ZSFs (see Clarke and Kendall, 1988 for sampling details). Each sediment core sample was vertically partitioned to allow infauna to be processed from the 0-2, 2-5, 5-10, and 10-15cm sediment depth intervals. Infauna from the 0-2cm interval were retained on a 0.25mm sieve, whereas the deeper

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sediment fractions were washed through a 0.5mm sieve. Infauna were picked and sorted to the class/order taxonomic level, then separated into discrete size classes (0.5, 1.0, 2.0, 3.35, and 6.35 mm) by a modified wet-sieving procedure described by Carr and Adams (1973). Wet-weight biomasses were then determined and converted to grams/square meter.

Demersal fish food habits samples were collected at each study area during ongoing fisheries resource investigations by the University of Washington during July 1987 (see Dinnel et al., 1988 for sampling descriptions). Demersal bottom-feeding fishes were separated from the total catch at each trawl station and sorted into species size classes (5-9.9, 10-14.9, 15-19.9, 20-24.9, 25-29.9, 30-34.9, and >35cm Standard Length). Stomach contents of fishes in each size class sample for a given location were pooled and processed as described by Borgeson (1963). Food habits samples were sorted to major taxa, size-sieved, and wet-weighed in the same manner as the benthic samples. Predator fish size class samples were grouped by cluster analysis (Bray-Curtis similarity coefficient, group average sorting) according to their relative prey size exploitation patterns. Prey size exploitation patterns were then used to estimate vulnerable infaunal prey sizes for each predator group.

The benthic data set was subjected to a data reduction and analysis sequence using cluster analysis (Bray-Curtis similarity coefficient, square root transformation, group average sorting), which identified benthic "strata" based on station similarities in terms of biomass quantities and benthos size characteristics. Strata were determined for four cumulative sediment depth intervals (0-2, 0-5, 0-10, and 0-15cm), which corresponded to estimates of potential foraging depths for individual demersal fish predator groups. Trophic support values were calculated as that portion of the total biomass in a benthic stratum within the vulnerable size range and available foraging depth range for each predator group.

Results and Discussion

Characterization of the benthos

Qualitative differences in benthic community structure were readily apparent among the four ZSF study areas. Polychaetes represented a major faunal component at each study site, and contributed substantially to the foraging base within the available and vulnerable zones identified. At the Bellingham Bay ZSFs, bivalve molluscs, primarily Axinopsida serricata, were a dominant component of the benthic assemblage. In comparison, bivalve molluscs comprised a much smaller portion of the benthic biomass at the Nisqually area study sites. Bivalve biomasses were particularly low at Devils Head ZSF stations. In contrast, ostracods and other small crustaceans (cumaceans and amphipods) were present in substantially larger quantities in the Nisqually area than at Bellingham Bay. Ophiuroids were essentially absent at the Ketron Island ZSF, but were present in notable amounts at the remaining sites.

In terms of total benthic biomass the Ketron Island ZSF displayed greatest mean wet-weight (approx. 112 g/sq m), whereas the Devils Head ZSF exhibited the lowest standing crop (approx. 65 g/sq m), and Bellingham Bay biomasses were intermediate. Vertical and size distribution of benthic biomass in the sediment column varied among the study areas. Figure 1 depicts the generalized ZSF specific distribution of mean benthic biomass among the various size categories for each discrete depth zone. This illustration can be used to compare the potential trophic support both available (in the appropriate size range) and vulnerable (in the appropriate foraging depth zone) to given predator feeding groups at each study area. Large differences are apparent between the two Nisqually sites, particularly in the size distribution and depth partitioning of 1mm and 6.35mm benthos. Biomass in the 0-2cm sediment depth layer displayed highest mean values at the Ketron Island ZSF. In Bellingham Bay, the size distribution of biomass is similar between study areas down to 5cm, except in biomass magnitude. A notable increase in large benthic biomass particles (size >3.35mm) occurs at the south ZSF relative to the north ZSF at sediment depths greater than 10cm.

Food habits analysis.

Although dominated by English sole (Parophrys vetulus), the overall trawl catch also contained Dover sole (Microstomus pacificus), rex sole (Glyptocephalus zachirus), butter sole (Isopsetta isolepis), rock sole (Lepidopsetta bilineata), starry flounder (Platichthys stellatus), and snake prickleback (Lumpenus sagitta). English sole diets were found to consist primarily of polychaetes, bivalve molluscs, euphausids/mysids, amphipods, small crabs and shrimp, and ophiuroids. Ostracods and cumaceans were important prey items in several samples. Euphausids and mysids, which are facultative members of the benthos, were a notable dietary component only at the Devils Head ZSF.

Seven prey exploitation patterns were discerned among the fish species size class samples. None of the predator groups classified by cluster analysis utilized predominantly small prey (less than 1.0mm = Group I prey size exploitation pattern). Five groups were identified based on their modal prey sizes as having fed upon primarily intermediate sized prey (in the 1.0 to 3.35mm size range = Groups IIA-E prey exploitation patterns). Two additional predator groups were found to have fed predominantly on large prey items (3.35mm or larger = Group IIIA and B prey exploitation patterns).

In general there was a close correspondance between observed food habits and composition of the benthic assemblage at each study site. This relationship was evident not only in the taxonomic composition of the diets and available benthos, but in the size characteristics of the infauna present in the stomach contents as well as in the sediments. For example, a bimodal size distribution was noted for the benthos only at the Ketron Island study ZSF. A similar bimodal size distribution (biomass peaks in the 1.0 and 3.35 mm size categories) was apparent in the prey of several English sole samples taken from the Ketron Island ZSF (Group IIC). Another example

of this relationship is seen in the foraging habits of starry flounder (Group IIB) in Bellingham Bay, where their diets matched infaunal size distribution and taxonomic composition within the top 5cm of the sediment column. The benthos here consisted to a large extent of Axinopsida serricata in the 2mm size category.

Benthic resource analysis

Figure 2 depicts the spatial array of benthic infaunal biomass potentially available and vulnerable to four of the observed feeding groups within Bellingham Bay. In general, foraging habitat potential observed for Group II predators showed a north-south gradient of decreasing prey biomass potential, with markedly lower biomass within the top 5cm through out the southern two-thirds of the ZSF. Higher trophic support in the 0-5cm available zone primarily reflected the presence of 2mm and 3.35mm bivalves (Figure 1), and may be a consequence of trawling activity disturbances of the bottom. Neglibible differences in potential trophic support were apparent for Group III predators within the Bellingham Bay study area, primarily due to the availability of polychaetes larger than 3.35mm at 5-10cm sediment depths.

Marked differences in biomass were apparent between Devils Head and Ketron Island ZSF's, particularly within the top 5cm of the sediment column (Figure 1). Benthic foraging habitat potential was depressed at Devils Head, which may be a consequence of intense predation pressure attributable to higher abundances of small demersal fishes at this site (Dinnel et al., 1988). Conversely, generally higher foraging habitat potentials observed at Ketron Island may reflect lower levels of predation due to lower abundances of small-sized demersal fishes. Fishes found at this site were primarily large size classes of English sole (Dinnel et al., 1988).

Conclusions

The results clearly documented close correspondance between benthos and foraging habits of fishes at each of the study sites. Evaluations of benthic habitat quality from a trophic support standpoint lead to recommendations for potential disposal site locations or site boundary alterations to optimize available trophic support for resident and transient demersal fishes. Based upon a north-south gradient of decreasing trophic support potential at Bellingham Bay, we recommend consideration of the south ZSF as the preferred site, with the site to be located in the south-west corner of the ZSF. At the Nisqually ZSF's, the Ketron Island ZSF exhibited higher trophic support potential than the Devils Head ZSF, although observations of relative fish abundance indicated higher utilization of the Devils Head ZSF by demersal predators. Active foraging by smaller-sized demersal predators at the Devils Head ZSF suggests that this area may be functioning as a nursery area to a greater extent than the Ketron Island ZSF. Small adjustments in site boundaries within each of the Nisqually ZSF's can optimize trophic support considerations. It should be pointed out that other potential natural

resource and human use concerns must be balanced against trophic resource concerns in the final site selection determination.

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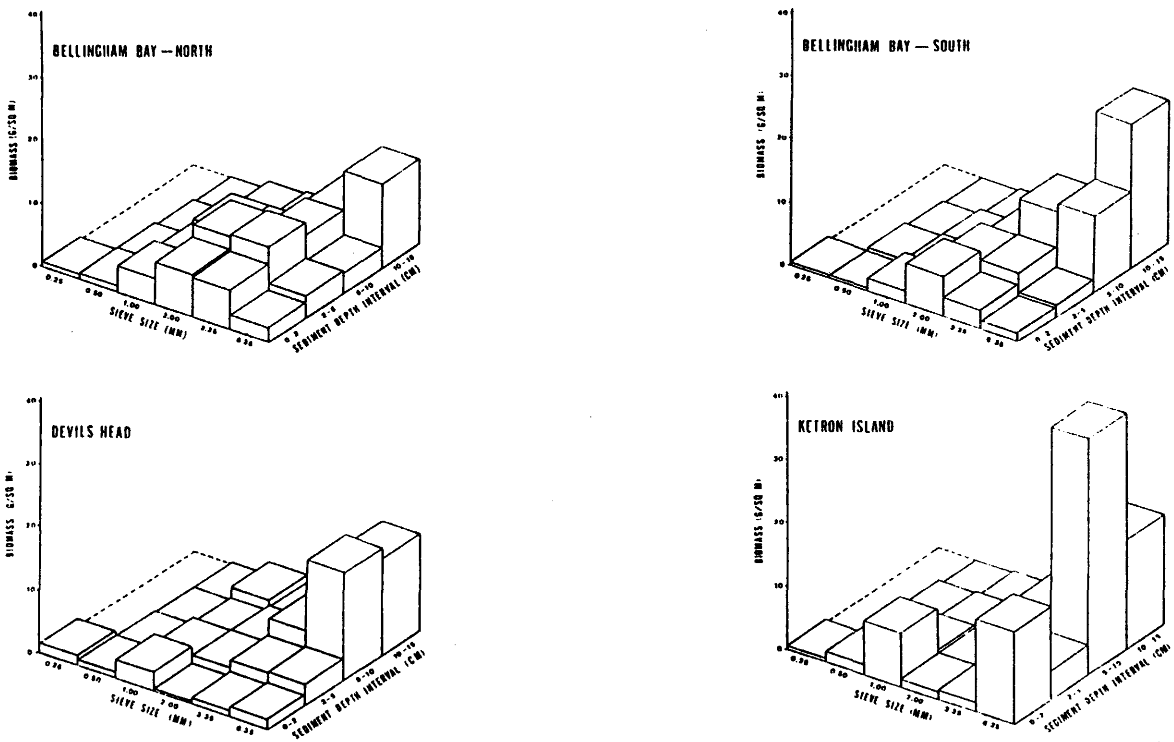

Figure 1. Three dimensional plots of mean benthic biomass accross size categories and sediment depth intervals for each of the four Zones of Siting Feasibility evaluated in North and South Puget Sound. Note that biomass in the 0.25mm size category was measured only for the 0-2cm depth interval.

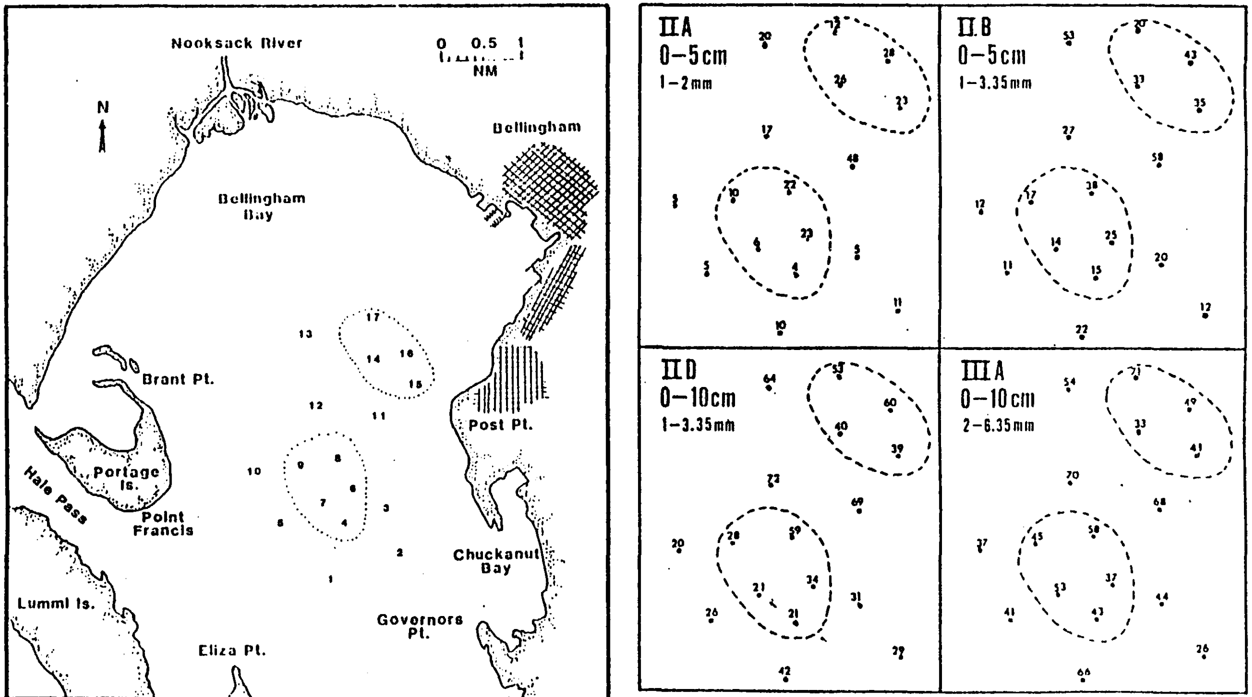

Figure 2. Vicinity map on left depicts Bellingham Bay Zones of Siting Feasibility with box core stations. Figure on right depicts spatial arrays of benthic feeding habitat potential for four of the identified predator feeding groups. Values in grams/square meter (wet weight).

LEGEND:
- Predator Feeding Group: IIA, IIB, IID, IIIA
- Available Zone (foraging depth): 0-5cm, 0-10cm
- Vulnerable Sizes: 1-2mm, 1-3.35mm, 2-6.35mm

Balancing Waste Disposal and Fishery Resource Impacts: A Comparison of Methods[1]

Shelley C. Clarke

Introduction

In recent years a trend has developed to assess the ecological impact of human activities on the environment by means of quantitative guidelines. The movement began with drinking water quality standards, progressed to standards for marine water quality and is now expanding to include standards for allowable impacts on living resources. Proponents of such guidelines argue that they increase accountability and consistency in management decisions by allowing laypeople to easily evaluate agency procedures (Packham 1984; Bibko 1976). These guidelines either identify specific resources to be protected or set limits on the impacts of harmful substances or activities. Although they are based on scientific information, the guidelines themselves are not necessarily scientific statements (Noss and Marks 1981). Rather, they are policy instruments to be used in specific contexts with appropriate caution.

According to conventional terminology, a guideline is a numerical statement of an acceptable condition or impact and a standard is a guideline fixed by law (Cabelli 1983). This paper presents two guidelines and one standard which are currently used in decision-making for dredged material disposal. It also outlines two other quantitative techniques for balancing waste disposal and impacts to fishery resources. For each case, an example is provided using local data to illustrate the technique. These examples are not meant to propound these indices as suitable for local policy but merely to focus attention on how such indices are developed and the advantages and disadvantages associated with their use. This type of consideration may encourage further research on more efficient and accurate alternatives.

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Important Flatfish Populations

This guideline was formed in December 1986 by the Washington Department of Fisheries (WDF) in response to inquiries as to what would constitute an important flatfish population. The Seattle District Army Corps of Engineers (COE) requested this guidance in choosing dredge disposal sites in the Puget Sound Dredge Disposal Analysis (PSDDA) project (Bargman 1987). Since WDF had not yet begun its finfish resource surveys, the only available data was from commercial fishing records. The guideline, which WDF calls a "critical density", is therefore formulated on the density of flatfish required to support a commercial fishery, in this case, the English sole fishery. According to WDF records, 28.63 kilograms (63 lbs.) per hour is the minimum catch rate which will induce a trawler to set a net. The average area swept per hour in this fishery is considered to be approximately 5 hectares, thus the minimum catch per hectare is calculated to be:

28.63 kg/hour x 0.2 hour/hectare = 5.73 kg/hectare.

Assuming the average commercial flatfish weighs .91 kg (2 lbs.), the critical density for a commercial flatfish fishery is approximately 6 fish per hectare.

WDF presented this figure to the COE but cautioned that "certain areas may be utilized...for specific life functions including feeding, rearing and spawning. These areas may subsequently be considered critical habitat and subject to different [guidelines]." (Blum 1987). This quantitative guideline, though formulated for the PSDDA project, was considered but not utilized in the draft siting decision (COE 1988). In fact, in every season sampled, PSDDA sites in all three Phase I locations exceeded 6 flatfish per hectare (Dinnel et al. 1986).

Important Crab Population

A similar sequence of events resulted in a WDF guideline for an important Dungeness crab population. PSDDA requested WDF provide them with a numerical criterion to guide their siting decisions. WDF contacted University of Washington fishery researchers who had data from recent north Puget Sound resource surveys. These data were compiled in a bar chart that showed number of crab per hectare at each of 22 stations. On the basis of this chart it was suggested that a naturally occurring crab density which was dramatically greater than background densitites could be tentatively set at 100 crab per hectare (P. Dinnel 1987).

This figure eventually was given to the COE with similar cautions that "critical habitats" merit special treatment in siting decisions (Cahill 1986). Unlike the flatfish

guideline, the crab guideline was articulated in the siting deliberations. No PSDDA sites exceeded the criterion but the Navy's originally proposed confined aquatic disposal (CAD) site surpassed the guideline in each sampling season (Dinnel et al. 1986). Although the 100 crab per hectare guideline did not alter the PSDDA siting decisions, it strengthened the identification of the Navy's CAD site as "crab condo"(Haley 1986). This, in combination with other factors, resulted in relocation of the disposal site to an area of lower crab density.

Allowable Impact to Crab Populations

The Washington Department of Ecology (WDOE) had to confront the issue of protecting crab populations in issuing the Water Quality Certification for the Navy Homeport Project. The permit states that approval for the second year's disposal is contingent upon demonstrating that the site has a mean annual density of less than 100 female adult crab per hectare and such crab are less than 5% of the total female adult crab population in a specified area within Port Gardner (WDOE 1987). These standards reflect the WDF "important" population figure with the additional stipulation that the 100 crab refers to adult females. The 5% figure represents the maximum percentage of the area's adult female crab the project is allowed to impact. This standard was developed using rough calculations to determine that the proposed disposal area occupies about 10% of the bay's area. It was then decided that the site should have less than half the average crab density of the bay if, as a worst case assumption, all crab in the disposal area would be killed (Elwell 1988).

Protection of crab resources in the WDOE Water Quality Certification involves a two-part test and either standard could be more conservative depending on population distribution and size. For example, if adult female crab are evenly distributed and each hectare in the disposal site has 75 adult female crab per hectare, the total number of crab in the disposal site would be approximately 7650. Currently, the best estimates place the adult female population in the Port Gardner area somewhere between 54 and 197 thousand crabs (Wainwright 1988), and 7650 is 21% and 6% of these estimates, respectively. For this hypothetical situation, the 5% standard could negate the permit whereas under the 100-crab per hectare standard, it would be approved. However, it is common for adult female crab to aggregate (Dinnel et al. in prep.; Orensanz and Gallucci in press). Under these circumstances it is conceivable that 100 crab per hectare could be the limiting standard. If the disposal site crab total was under the 5% standard, an aggregation within the site could drive

the average density per hectare above 100 crab and affect permit approval.

Indices of Degradation

Recently there has been a movement toward defining environmental impacts within the context of natural variation in population levels. The National Oceanic and Atmospheric Administration (NOAA) has developed several "indices of degradation" to address this issue (O'Connor and Dewling 1986). Although such indices are not yet being used, the concept is interesting and has potential in environmental impact assessment.

As a local example, one of these indices is applied to data collected for the purpose of modelling the impact of dredging on Dungeness crab in Grays Harbor, Washington (Armstrong et al. 1987).

The index (I) is defined: $I = \left[\dfrac{\bar{x} - t_{(0.1)} s_{\bar{x}} \sqrt{(1/n)(1/m)}}{\bar{Y}}\right]^b$

where $\bar{Y}$ = mean number of crabs in the area during dredging, averaged over m years

$\bar{x}$ = mean number of crabs in the area before dredging, averaged over n years and calculated to be 2,198,478 using WDF crab landing statistics for Grays Harbor and offshore from 1943-1976 (n=34). (WDF 1976)

$s_{\bar{x}}$ = standard deviation of x

$t_{(0.1)}$ = one tailed t statistic (df = n-1)

b = 1.74 (assuming a replacement rate of 1)

(After O'Connor and Dewling 1986.)

The model of dredging impact suggests a total loss of 202,000 crabs (using the linear, confined, mean estimate) over a 4 year period. $\bar{Y}$ can then be calculated as:

[(2,198,478) x 4 -(202,000)]/4 = 2,147,978

and I is given by

$$\left[\frac{2,198,478 - (1.308)1,225,401 \sqrt{(1/34)(1/4)}}{2,147,978}\right]^{1.74} = 0.9306$$

According to the index scale, 0.9306 or any number between 0 and 1 is interpreted to be within the normal zone of population variation.

Risk Analysis

Another technique for balancing waste disposal needs against fishery resource impacts is that of risk analysis. This process involves identification of hazardous constituents of the dredged materials, characterization of the

risk to the ecosystem through exposure and suseptibility calculations and managing the risk by translating the scientific results into a social and regulatory framework. Risk characterization involves generating a dose-response curve from bioassays on established indicator organisms (amphipods, mysids, oyster larvae, etc.). Risk characterization also requires calculating ecosystem exposures with various disposal options. Exposure assessments and dose-response assessments are then combined to estimate the probability and extent of adverse effects associated with contaminant release (Tetra Tech 1986). The results are a ranking of disposal options by risk.

Although risk analysis was examined in a PSDDA report (Tetra Tech 1986), PSDDA's goal was to designate unconfined open water disposal sites for basically clean sediments. Therefore, the PSDDA project used a qualitative mapping of biological resources for its disposal site selection. Risk analysis is especially valuable in disposal decisions concerning contaminated sediments since it is designed to rank the risks of various types of disposal options (e.g. unconfined, confined, nearshore, upland). Its utility will depend on whether the model is robust with slight changes in dose-response and exposure variables. If not, other considerations may weigh more heavily in the final decision (Tetra Tech 1986).

Discussion

The indices outlined above have both advantages and disadvantages in marine policy formation. Advantages include 1) easily developed and understood guidelines or standards, 2) facilitation of decision-making and 3) easily defended policy. However, each of the techniques outlined above has its own particular problems. The guideline of 6 flatfish per hectare is based on commercial fishing records for one fishery which may have little relevance to natural population sizes. In addition, abundance sampling for guideline comparison is heavily gear dependent. Although the guideline of 100 crab per hectare is based on standardized resource survey data, it has a similar problem with gear dependency. However, it does serve to protect resource aggregations and identify preferred habitats. The allowable impact standard for crab (5%) avoids inherent ties to any particular gear type, addresses the project's impact on the entire population and allows the impact to change with population fluctuations. Which of these standards is used in Port Gardner will depend on the crab population distribution and size. O'Connor and Dewling's (1986) index also considers the impact in a population context but only uses population variance in its assessment. Status of the fishery at the time of impact (e.g., recovering versus sustained high production)

can be an important component of the ultimate effect. The technique of risk analysis can be highly subjective since the result is heavily dependent on the included variables and their weighting.

The first step in grappling with the complex and controversial issues in impact assessment is to realize that there is no magic number. The best approach may be to consider a variety of indices as well as qualitative methods, keeping in mind their particular drawbacks and biases, rather than depending on one or two. Ultimately, better data bases must be developed to respond to the information needs of environmental policy. Quantitative techniques can effectively facilitate decision-making but should be used cautiously so as not to compromise the science upon which they are based.

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Summary Statement

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Environmental planners are frequently surprised to discover how little we really know about bottom living resources in Puget Sound. What limits their production? Dissolved oxygen and water quality? Habitat, cover and food? Predation and fishing? How many crabs and sole are there? What is the population value of 10 crabs; 100 crabs? Where are they located? We've found some "crab condos;" but where are their "children's playgrounds" and their "community kitchen?"

Given these uncertainties, how do we assess adverse effects to living resources? Often, we do not -- we simply do the best we can to avoid them. And where we can't avoid them, management decisions are not easy.

In some areas, we are making progress. Dissolved oxygen predictions can lead to field monitoring of dredging, and to management decisions to ensure fish passsage, and to minimize the magnitude and area of dredging influence. We are beginning to quantify the food value of the bottom to bottom-feeding fish and shellfish. Benthic areas with higher food value can then be selectively avoided, and the value of an impacted area can be monitored over time. We are beginning to overtly express our value judgments used in management decisions, and to objectively assess the utility of the resulting standards and guidelines.

However, we all recognize that key information about living resources is still missing. While the past impetus for obtaining this information has often been construction development or waste management activities, we now see that the subject deserves broader funding and longer-term assessment. Unless resource managers better understand their system, management decisions of all sorts will continue to be hampered. And until then, decision guidelines and standards will necessarily have a greater component of administrative policy than science.

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