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PROCEEDINGS

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The mission of the Puget Sound Water Quality Authority includes the dissemination of the results of research on issues pertinent to the health of the Sound and its inhabitants and to the management of its resources. Periodic research conferences have been by far the most significant and successful means of achieving this goal. In 1988, 1991 and 1995, these conferences brought together scientists from agencies, universities and consulting firms, resource managers and other decision-makers, and members of the interested public to review the current findings of the day. The conferences, and the accompanying proceedings, have highlighted the latest trends in basic and applied research, and brought to a wider audience many studies and findings that otherwise might have been confined to relative obscurity in an institution's or department's "grey literature."

Presented by the Puget Sound Water Quality Authority and co-sponsored by state and federal agencies, universities, and private businesses, the third conference on research in Puget Sound, *Puget Sound Research '95*, was held on January 12-14, 1995, at the Meydenbauer Center in Bellevue Washington. It featured speakers from both sides of the border and the latest research on water quality and habitat issues in the Puget Sound/Strait of Georgia region. Over 700 attendees joined speakers in a variety of presentation formats, including plenary and luncheon addresses, concurrent paper sessions, panel discussions of special issues, and student and poster sessions.

Here, in two volumes, are the proceedings of the conference, including panel and plenary sessions transcribed verbatim. You are encouraged to contact the authors/presenters for further information and updates on any of the subjects discussed in these pages.

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PROTECTING PUGET SOUND: A CHALLENGE FOR SCIENCE

Dr. Usha Varanasi
Science Director, Northwest Fisheries Science Center
National Oceanic and Atmospheric Administration

The complex biological and oceanographic problems that threaten Puget Sound pose a great challenge for science. However, to make science significant in the political process and the environmental management strategy is an additional challenge that scientists face. I hope to give you an overview of some pollution issues in Puget Sound that are indeed a challenge to both science and scientists.

Major Global Threats to Puget Sound

Following are some of the major global threats that have been defined by recent treaties on marine biodiversity: overfishing; altered physical environment, which includes diversion of fresh water and degradation or loss of habitats (e.g., wetlands); pollution of the sea; increased UV radiation; and introduction of alien or exotic species. The introduction of exotic species has become more prevalent as oceanic transportation increases—we bring not only desired guests and goods from faraway places, but also unexpected creatures that may take over their new habitat. Accidental introduction of pests and diseases, such as the Japanese oyster drill, can threaten indigenous species. This threat can also arise from some well-intended introductions, such as the release of hatchery-reared salmon, which end up causing damage to wild salmon stocks. Introductions are often not properly managed. Smolts released from the hatcheries, for instance, may not be fit for life in the wild. Or sometimes large numbers of smolts are released in a very short time, thus crowding migration corridors and creating a shortage of prey. Such mismanagement can result in the decline of both hatchery and wild stocks, as well as continued dilution of genetic diversity. The extensive loss of habitat in Puget Sound also jeopardizes the health of marine ecosystems. For instance, wetlands show a 76 percent decrease from about 100 years ago. Since we don't know what percentage of critical habitats are needed for sustainable productivity, we don't know how much we can "afford" to lose. We do know, however, that adverse effects on marine animals are occurring as a result of what we have lost already. These changes occur partly because of physical alterations of the environment (e.g., building of dams on rivers) that destroy critical habitat. Pollution, industrialized activities, and changes in the shoreline also have an adverse impact on marine habitat.

All these elements constitute a major threat for most urbanized coastal areas, and Puget Sound, unfortunately, is no exception. As you may know, parts of Puget Sound are listed as the most polluted sites in the United States, so clearly this area is not as pristine as we would like it to be. But we also have the good fortune to have a large number of scientists, natural resource managers, and dedicated public interest groups to help us identify which threats should concern us most and how we should address them.

Status of Salmonid Stocks

Over the last 100 years salmon stocks in the Pacific Northwest have declined. In Puget Sound, 21 percent of salmon stocks are believed to be depressed, and 5 percent of stocks are considered to be in critical condition. Stocks for the Washington coast are healthier, with only 7 percent of stocks believed to be depressed and no stocks in critical condition. However, both Puget Sound and the Washington coast have a high percentage (29 percent and 37 percent, respectively) of stocks whose status remains unknown.

What is causing the depressed condition of these stocks? Both anthropogenic and natural factors can affect salmon stocks. Overharvesting, hydroelectric dams, hatcheries, and habitat loss have been identified as four interlocking anthropogenic factors that could be affecting the anadromous species. But we also know that oceanic and climatic conditions are important factors in the ocean survival of salmon.

It is not only the anadromous species and stocks that are declining, however. We find in Puget Sound that some of the groundfish stocks are also declining. For instance, Pacific whiting stocks have declined dramatically since the early '80s.

When addressing the condition of salmon and other stocks, scientists must try to collect information on both anthropogenic and natural factors, as well as the relationship between these factors. The scientific community and the public often focus on the anthropogenic factors because we know we can manage and regulate these activities, and we are resigned to the futility of controlling naturally occurring changes. However, just knowing the impact of natural variations allows us to be more adaptive in our management of the anthropogenic activities that we can control.

In order to examine all the factors that may affect stocks, a multidisciplinary, cooperative approach is required. Unfortunately, often the scientists who work on the natural events and fluctuations—oceanographers, hydrologists, ecologists—don't team up with the toxicologists and other environmental scientists, and vice versa. This is partly because the disciplines have tended to be more specialized. However, we must combine these disciplines and work together to address these complex issues if we wish to protect our natural resources.

Challenges for Science

The challenges for science are clear. We need to clearly link threats to the effects we see in living marine resources. In the Puget Sound region, the public is much more sophisticated about understanding the effects of urban pollution than in many other parts of the country, but we still have a tendency to believe that only certain anthropogenic stressors are causing the adverse effects in marine organisms.

It is also necessary to determine threshold levels for habitat loss, harvesting, and contamination. In some cases, the level may be zero. In addition, we need to predict unacceptable threshold levels for any particular anthropogenic stress by using appropriate measurements. If we have solid science to support our conclusions, then we can face the biggest challenge, which is to convince those in management and in the political process to link scientific information with management and political action to prevent or mitigate threats and restore degraded watersheds.

Marine Pollution

Quite often I am asked why chemical contamination is considered to be the major anthropogenic threat to marine organisms and coastal ecosystems when there are so many other threats facing these resources. Chemical contamination has a dual impact because it poses both ecological and human health risks. Contaminants can jeopardize the ecology of marine species by affecting the health and survival of individuals, which eventually will impact populations. Contaminants can also be an immediate health risk to humans by accumulating in seafood species. This dual impact is always at the focus of marine pollution research, and it requires a considerable amount of carefully worded scientific information so that we don't frighten people unnecessarily, and at the same time can take action when there is a threat to either an ecosystem or to human health.

There are many ways to address the two-pronged threat of chemical contamination. One of the approaches we have had success with is to use multiple disciplines; to study a broad spectrum of contaminants and a wide range of marine species; and to do research, monitoring, and method development. This approach, which uses a combination of multidisciplinary field and laboratory studies, has enabled us to determine links between effects observed in indigenous species in Puget Sound and classes of chemical contaminants. The types of deleterious effects that are either documented or studied in Puget Sound are diseases such as liver tumors in fish, reproductive dysfunction in benthic fish, immunological dysfunction in salmon, marine mammal mortality, and growth impairment in young animals.

Goals in Chemical Contaminant Research

In our efforts to assess the links between contaminants and biological effects, we must identify which chemicals are consistent risk factors out of a large suite of chemicals. The current state of knowledge is such that scientists are able to measure a large number of chemicals at very low levels with sophisticated measurements, and hence analyze many chemicals to a very minute level. But we often do not know the levels at which the chemicals are capable of causing effects in marine organisms, and which chemicals we

should be really focusing our attention on. By identifying chemicals that are risk factors for adverse biological effects, we can set correct priorities. Our resources—money, people and time—are limited, after all. In addition, we must determine acceptable and unacceptable threshold levels for the chemicals identified as consistent risk factors.

The most important goal in this area, however, is to develop a diagnostic or predictive capability. By developing simple yet reliable tests, we may be able to predict how an ecosystem will react to various anthropogenic and natural effects. The ability to predict and then prevent deleterious effects calls to mind the adage, "A stitch in time saves nine." I think in the field of chemical contamination, given our experiences with Superfund sites, if we can prevent and mitigate certain effects of pollution and degradation, we perhaps will be able to do a better job of preserving our ecosystem. This is more time- and cost-effective than allowing watersheds to become so highly polluted that small improvements require many years and tremendous resources. Developing diagnostic tools should be one of the biggest challenges of the environmental sciences.

Liver Tumors

Studies of chemical contamination that I will discuss below have been conducted by the scientists of the Environmental Conservation Division of the Northwest Fisheries Science Center. These studies are an excellent example of scientific data that can be generated by addressing the goals of chemical contaminant research I described above. One such study is the research on liver tumors in bottomfish. After many years of work, it has been shown that the liver tumor is strongly linked to chemical pollution. The consistent risk factors for the liver tumors are the known anthropogenic pollutants, such as aromatic hydrocarbons, as well as natural factors, such as the age of the fish. PCBs in general were rarely significant risk factors, a finding that not only applies to Puget Sound but to bottomfish species from a large number of areas in the coastal United States. Our research on the consistent risk factors gave us some understanding that sometimes chemicals that are converted (metabolized) and removed from the body may be greater risk factors than those that accumulate in tissues. Just because we can measure a chemical in an animal from a contaminated area does not necessarily mean that particular chemical is a significant risk factor. The age of the fish being a risk factor showed us that tumors themselves are not very good biomarkers, or diagnostic tools, because they happen many years after the fish have been exposed to contamination. While liver tumors can be good markers in fish that reside for long periods in a certain area, they are not very good for young fish or fish that move from one area to another.

Better biomarkers are some of the early effects, such as DNA damage and pre-cancerous lesions. DNA damage is a broader term and can be recorded by a variety of tests. In our research, we have tried to use those tests that show DNA damage that is specifically due to chemical pollutants. For example, DNA adducts (chemicals bound to DNA) are found in a variety of species from sites having high levels of contamination. One of the guiding principles or ground rules for developing biomarkers is that the effects must be specific to the stress or chemicals we are working with. They should be dose-responsive so that we can detect contamination gradients in various watersheds; and the biomarkers should also be reliable indicators of serious health effects in biota. In addition, those biomarkers that are reversible serve as good tools to test improvements in ecosystem health when damaging pollutants are removed or reduced in an area, or when a watershed ecology is restored.

Reproductive Dysfunction in Fish

Although individual fish in polluted sites show liver tumors and other serious diseases, a major concern for fishery resources is whether the reproductive capabilities of the species are impaired, and thus whether the population is at risk. We found that female fish that lived in contaminated sediment, regardless of whether they have liver tumors, seemed to have significantly impaired reproductive processes. Gonadal development or sexual maturation was retarded, spawning success was less, and abnormalities were present in larvae. Hydrocarbons were linked to impaired sexual development. In addition, our studies suggest that

alteration in sex hormone production may serve as a biomarker for retarded ovarian maturation in fish inhabiting polluted waters.

We have conducted several studies on reproductive impairment in English sole, and our research shows that if all other changes are kept constant (recruitment, etc.), certain contaminated sites would indeed show a significant decline in population. Whether these results are significant enough to affect management strategy remains to be seen, but the information can be used in establishing fishing thresholds, if projection models are appropriate. Data from studies such as this can provide more quantitative information, which makes it easier to convince people of the validity of the data. Such data are also easier for managers to use.

Immune Dysfunction in Fish

So far, we have talked about the effects in bottomfish, but it is the salmon that have been always a major concern in the Pacific Northwest. We wanted to test whether juvenile salmon migrating through contaminated sites in Puget Sound would experience any kind of adverse effects from contaminant exposure. We found the young fish do pick up chemicals during their brief residency in polluted estuaries, and that they do show altered immune function. Particularly, the young fish show altered immune competence and increased susceptibility to disease. In addition, we found that chemicals, including hydrocarbons and PCBs, cause similar dysfunction in the laboratory. Three important questions follow. Which contaminants cause effects in polluted estuaries? How long do the immune dysfunction and decreased disease resistance persist? And how do they affect early ocean survival of salmon? Ongoing and future studies will attempt to address these questions.

Contaminants in Marine Mammals from Coastal Waters

Because there was a great deal of concern about gray whale mortalities in Puget Sound, we analyzed a broad spectrum of chemical contaminants in stranded gray whales. We found that levels of chemical contaminants in gray whales from Puget Sound and the outer coast of Washington state, Alaska, and San Francisco were relatively low compared to levels in other marine mammals, such as porpoises and certain whales that feed on fish. We did not find region-specific profiles of contaminants in gray whales, suggesting that the level or types of accumulated contaminants were not related to pollution profiles at the site of stranding. We will continue to pursue studies on contamination and mortalities in various marine mammals to better understand the effects of chemical pollution in these species and determine whether certain marine mammals will serve as good indicators of ecosystem quality.

Assessment of Contaminant Effects in Puget Sound: A Multidisciplinary Approach

I would like to briefly address the application of the research results I have described. Using screening methods developed to rapidly assess the levels of contamination in sediment and biota and using various biomarkers as diagnostic tools, the combined information from several Puget Sound sites allows us to identify which areas have high levels of contaminants and thus high impact in terms of various adverse effects. For areas that have no detectable effects, we can conclude that we do not need to perform detailed chemical analysis or biological studies; however, these areas must be periodically screened to detect signs of degradation in the earliest stages.

The chemical screening methods and a suite of biomarkers are intended to provide a quick "snapshot" of the "health" of a watershed. This snapshot can then be used to select sites for more intensive monitoring and analysis, thus keeping the cost of doing watershed analysis within a reasonable budget and providing timely information. The major frustration I have as a scientist, and as part of a scientific agency, is convincing the management and regulatory agencies to take on new approaches and measurements such as these for testing in pilot projects. However, I should say that in recent years, working with many of the agencies such as EPA and other parts of NOAA, we have had some success in testing these new methods and approaches.

Conclusion

The most important challenge of a scientist is to be brave, honest, objective, and still be effective. It is a tall order, but it is happening because as we develop better scientific information, there is more respect and understanding from the agencies that regulate and manage our natural resources. The challenge to those who are in natural resource management is to work with scientists and use the best available information to assess the status of, and predict changes in, marine and estuary ecosystems. For the scientists, our biggest challenge is to assess relationships among observed changes resulting from human activities and natural environmental change. The challenge for both parties is to work together for the development and implementation of management strategies and regulatory policies that ensure the preservation, wise use, and enhancement of living resources in beautiful Puget Sound.

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SALMON: THE SILVER SHUTTLE

Tom Jay
Sculpter, Author and Co-founder of Wild Olympic Salmon and of North Olympic Salmon Coalition

To begin I'd like to offer a kind of framework of two or three images through which you might listen to my words.

I do a lot of catch-up reading, reading various little papers written by, especially, fish biologists and researchers into ecosystem dynamics. I read a lot of scientific papers mostly because in my restoration work I want to inform myself as to how the salmon are doing and what their life histories are about. In reflecting on my reading one day, I was struck by a Biblical image, the image of Moses. I imagined scientists, as a body, being Moses. I don't know if you remember this story, but when Moses went up on Mt. Zion to talk to God and get the tablets, it was a pretty intense experience for the fellow. And when he came down, he had a speech impediment. He couldn't speak, and he would even throw fits. So he couldn't convey the wisdom that he had gained from his conversation with God. Luckily his brother, Aaron, could understand him, though, and he translated for Moses. So Aaron would hold his rod and listen to Moses, then translate and speak to the people.

I don't pretend to be Aaron to the scientific community. I think that's a job that all of us need to take on—we all need to grab our staffs and to take the knowledge of science back to our communities.

But part of what I'm trying to do today is take the knowledge of science and translate it in a way that might be enfolded into local culture.

That brings me to my second point. I think one of the things that's happened in our culture is that we've gotten out of balance. We've turned culture into an item that you have to buy a ticket to go to. Yet I believe where it really belongs is in neighborhoods. It belongs in attached places, attached to people. So the other thing I'm trying to do today is to get you to understand the root sense of what culture's about. If you go back to the root of that word, it comes from an old Latin word that means "turning over the earth." And indeed cultures have this quality of taking what's old and what's gone before us and turning it back up into the light. So part of this little lecture today will be trying to get you to see that it's possible to have a local culture following salmon.

The last image I want to give to you as a framework for my discussion is this. We're at the end of this century, and the end of this particular millennium. A poetess friend of mine described our situation very succinctly. She said, "When you're in the middle of a paradigm shift, you have to remember to put the clutch in." I think that in our culture right now, every one of us knows that there's some radical change coming, though we don't know what that change will be. So I think it's time to put the clutch in and maybe just coast a little bit. Let's listen to what our hearts are saying and try to figure out what we're going to do when we let the clutch back out again.

We all know that salmon is the embodiment of the Northwest. It's emblematic of our land here. One author said it very well. He said, "The Northwest is anywhere salmon can get to." Salmon leap. Indeed, their very name means "leaper." It comes from an old root *salire*, which means "to leap." That root also gives us the words *salient, somersault,* and—my favorite cousin of the word salmon—*exaltation.* I don't think anybody can see a salmon going up a falls without feeling the exaltation in that motion.

The salmon's genius is to travel thousands of miles in its gyre, in its turn through the North Atlantic and North Pacific realms. It's the mystery of that journey that entices us. The salmon's genius is to travel these thousands of miles and return to its home place. It does this through a process of great sensitivities. It has rheotaxis, that is, sensitivity to currents. It also navigates the ocean by means of sensitivity to electromagnetic fields—at least, this is what the scientists think now. As they swim out into the North Pacific, they can actually encode the magnetic patterns in the earth's field, and they can trace that back home to nearly their stream of origin.

Once they're near their stream of origin, they use their fantastic sense of smell. They can actually smell the bouquet of the stones. They can discriminate parts per billion with their sense of smell. Each

species layers and weaves its life history into every watershed in the Northwest, and in a non-competitive way. Each species and stock uses discrete portions of the watershed. Sockeyes need lakes as nurseries as part of their life history. Silvers go in little streams. Chinooks go in mainstem rivers. Every salmon has a specific habitat it seeks out.

We are especially moved by the salmon's death. There is something that resonates in the human psyche about a critter that comes back and, in its final act of life-giving behavior, dies and gives its body back to the place it was born.

The salmon's role in the watersheds of the Northwest is just starting to be opened up. One study I read recently said that 50 percent of the carbon in Northwest streams is generated by the salmon bringing back marine carbon.

The salmon are also starting to be re-imagined as a keystone species. These Alaska grizzly bear are big because of the salmon. But if the runs in Alaska aren't big enough, the bears don't gain enough body fat. And if the bears don't gain enough body fat, the females will actually abort the cubs in their dens. So the salmon are critical to the survival of these creatures.

The grizzlies prefer to eat only the brains and roe of the salmon. As sentimental people we might think that's wasteful. But the Native American peoples see this behavior a little differently. They say the grizzly bear's just helping everybody else out. Because what the bear does is throw the salmon onto the bank and eat the brains and the roe, leaving something for raven, for weasel, for lynx and wolf, and for all the rest of the creatures. Far from seeing it as wasteful, the Native American peoples see the grizzly bear as a retrieval mechanism.

Of course, there are other creatures that use salmon. Jeff Cedarholm with the Department of Natural Resources, who is also on the faculty at Evergreen State College, wrote a really informative paper on coho utilization by various species of Northwest creatures. He documented 22 species of critter in the Northwest, including mice, elk, deer, water ouzel—creatures you wouldn't normally think ate salmon, but which at some point in their life history all use salmon as a food source.

I was traveling in our watershed one day with a local forester, and he took our group to an osprey nest. I thought he was taking us to this old-growth fir to show us the nest. That wasn't his intention at all. When we got there, everybody was looking up at the nest. He said, "Wait a minute. The real story's here around the base of this tree." And what we saw around the base of the tree was the scat of probably coyote, raccoon, lots of different predator species. He said, "See, what happens here is that the osprey bring a salmon back to the nest. And of course, the young of the osprey, just like our young, are always knocking their oatmeal on the floor." So he said the local denizens of this forest figure this out—this is a great lunch spot. He said, "Think about it this way: This is a transport locus; this is a way that the salmon nutrients get moved out into the forest ecosystem." I thought that was a pretty nifty thing.

I like to imagine the salmon as a kind of silver shuttle that weaves the rain-green world of the Northwest together. It starts in our home streams, in the fresh water of our home streams, travels to the ocean, gathers nutrients, comes back, and by dying gives those nutrients back to its home.

The life histories of the salmon are just as varied in the fresh water as they are in the ocean, and in their spawning return. Each species has a very different way of adapting to the local watershed. I can't go into this in depth now, but a good example is found in the variety of cues that prompt the various species to begin their outmigration. Silver salmon, for instance, outmigrate in response to timing cues. They have kind of an internal clock, which dictates that at around 18 months they all go out to sea. Chinook salmon, on the other hand, go out to sea when they reach a certain size. Chum salmon rise up from the gravel and go immediately out to sea. So each species has its own strategy for leaving the freshwater environment.

The thing about salmon that strikes me most in an emotional way is that a thousand years ago there was a silver garland around the planet Earth. Every temperate watershed in the northern hemisphere had salmon. And the people there were greatly dependent on salmon. It's no wonder, considering the stark conditions left by the last Ice Age, the land scoured and leveled by glaciers. Imagine our ancestors wandering into this devastated landscape. Luckily for them, the salmon was wandering in at the same

time. Salmon were probing those devastated watersheds from refugia both north and south of where the glaciers had occurred.

So it can be said we co-evolved with the salmon, at least culturally. If you go back in the myths and legends of all the cultures of the north temperate zone, you'll find mention of salmon. The Irish thought they were the wisest creature in the universe. The Native Americans in the Northwest said they were the most generous beings. You probably don't imagine Swiss people having salmon, yet at one time salmon came to Switzerland—but they'd always be beaten up there. A cultural echo of this remains in Switzerland because there's a cuisine in there based on beat-up, bruised salmon. As a result, there are special markets for people who can find bruised-up salmon for the Swiss.

This co-evolution with salmon is really nicely expressed by this photograph by Natalie Fobes. This is from a site in Siberia. All that clothing is made from salmon skins. Those harpoons are used to fish salmon on the Kamchatka Peninsula. This is a culture that's been dwelling with salmon for about 10,000 years.

The people of the Northwest believed that salmon were actually human beings, and they lived in houses, each according to its species, in villages far out to sea. When they were in those villages, the salmon were people like you and me. But once a year, they would decide that it was time to go visit us, their friends on the land. And just like anybody would when paying a visit, they brought a gift. Their gift was to put on these cloaks of salmon in return for the good treatment they received in their visits to us.

Northwest Coast peoples on our continent, as well as North Pacific peoples all the way over to Hokkaido, Japan, had first-salmon welcoming ceremonies. The ceremonies were very similar across cultures because the wisdom embodied in them was a basic wisdom of how to treat a resource. Here, the ceremony called for the first salmon caught to be taken to the village where it was butchered and prepared in a special way by the oldest matriarch. When it was presented to the people, the village speaker would make a great speech of welcome, saying how the villagers were so glad to see this emissary of the salmon people again. They treated that first salmon like royalty, carrying it into the village on a cedar mat and giving it a place of honor.

When the fish was cooked, a bit of the fish was passed around to every person in the village. In some traditions, some of the back fat from the salmon would be rubbed on the bellies of the children. I always liked this image because when the children welcomed the salmon into the village, they always would sprinkle their heads with eagle down, so I see this image of little fat children with shiny bellies and eagle down in their hair. It's a nice image. And when the feast was over, they would return the bones of the salmon to the creek, and make a speech of farewell, saying how glad they were that this emissary had come to visit them.

On the other side of the Pacific the Ainu people, who were the aboriginal peoples of Japan, had a very similar belief. The Ainu are just starting to reclaim their traditional connection to the salmon, because in the 16th and 17th centuries, when their homeland was conquered by the Japanese people proper, the Japanese sealed off the river mouths with weirs and refused to let the Ainu fish. Terrible starvation resulted. It's just in the last 10 years or so that the Ainu have been able to harvest a few salmon for religious purposes and revive their first-salmon ceremony, which is basically very similar to the Northwest Coast Indian salmon ceremony.

Now, one thing that the Ainu do a little differently from the Northwest Indians is that they have a window in their house, and they pass the salmon through that window, in front of the fire. They do that because in their cosmology, fire can see. It's as if our TVs were hooked up to the government, allowing Big Brother to watch us. What the Ainu have is Big Mother watching them, with fire serving as the eyes of the resource world. The fire reports back to the gods who control the resources what kind of treatment the salmon received.

To the salmon and the native peoples—and this includes our ancestors—the world was a vital and vivid world. It was a circle rolling ever forward in time. The people were located in a cycle. Theirs was a culture that was so in tune with the cycling that when native women would knead the flesh of the salmon

so it would dry properly and not rot, they would actually sing songs to the salmon to keep it happy. In their mind the salmon was vital and vivid until it was eaten.

Then we showed up. About the 19th century, Western culture arrived on the West Coast of the United States. And at first, we took our salmon mainly from the rivers, because our technologies of fishing and canning were rather primitive. But salmon quickly became a commodity, and by the mid-20th century, we had developed this commodity-oriented economy into a very intense enterprise. It was as if rather than rolling with the circle, we decided to break the circle open, mine its wealth and use that capital as start-up funds for moving on to another adventure. I believe we're just coming to the end of that paradigm.

As destructive as it was, there was still some beauty in the way we went about this intense enterprise. I was a commercial fisher for a while, and I have a deep respect for the people who fish. I was involved in a troll fishery. It's a fishery in which you catch the fish and clean them immediately. This is the high-priced restaurant fish.

This slide shows an older fishery, a traditional subsistence fishery. This is a chum fish wheel on the Yukon River, where this family catches dog salmon to feed their sled dogs and their family for the winter. And there are the traditional Native American fisheries that through the Bolt decision have been reinstated and are starting to flourish. Actually, as everybody knows, the tribes have become co-managers of the resource and have done a lot of fine work, especially on the watershed side of the fisheries.

The sports fishery is obviously suffering right now. The economy has even articulated itself more intensely in the sense that sometimes it's the roe that is more valuable than the flesh of the salmon. The market for salmon is a worldwide market. There is very deep pressure on the stocks now.

A curious thing has happened. In the final transformation of salmon into commodity, we've started to farm salmon. My co-author, Brad Matson, being an old fisherman, has a deep objection to farmed fish. I think he's right, because farmed fish don't have any ecological return address. You don't know where they're from. As a watershed restorationist, when I go into a restaurant I've gotten into the habit of asking the waiter where the salmon is from. Because I know if they're buying salmon that came from a watershed, then there's a connection, and there's an obligation to keep that watershed intact to produce that beautiful fish.

The paradigm we're stuck in now is the bottom-line paradigm. It's a paradigm that's worn itself pretty thin, even though it's persistent, as witnessed by the last election. But our economy is no longer connected in a really strong way to the resources. It's become more of a casino, where people are making side-bets on side-bets as to who's going to be successful, who's going to fail.

Contrast it with a subsistence fisher in Alaska. She's betting on herself. She's betting that she can catch enough fish to live for another year.

Yet underneath the harvest, and underneath even the commercial intensity that swirls around the salmon, there is a deep respect. Some of the best talk about the salmon resource I've ever heard has come from commercial fishers. They have a subtle enough vision that they can even recognize stocks as they come aboard their boat. They'll say, oh, this is a Skagit king, or this is a South Sound dog. They're very caring people, and many of them really care about the resources.

Now the shadow of the larger industrial economy, this circle-breaking that we've all been riding through the last 150 years, has other consequences. You people have been discussing it today. Logging obviously has taken its toll. The logging industry borrowed capital from the salmon industry; now they're turning around and starting to pay it back.

This slide shows placer mining in Idaho. This was once a fairly rich salmon stream. You can see the tons of material that were sidecast from the mining operation.

Then we get into some pretty weird scenes. This slide shows a salmon barge on the Columbia. Because of our need for cheap power, we find ourselves in the position of actually taking fish downriver in barges at a price that's—I don't think we even know how much it costs per fish.

This is a picture of some king salmon on the Elwha that were stricken with a gill disease because the water behind the dams heated up to such a temperature that these organisms were able to metabolize in the water and kill the fish.

This is a picture of gravel in the Dungeness. The whole Dungeness system has been loaded with gravel from past logging operations to the point where now all the different links, the necessarily connected moments of the life histories of salmon stocks in the Dungeness, have been broken. The river's kind of gone crazy. It'll take years for it to straighten itself out. In effect, a river of gravel has to come out of the Dungeness before the fish will really be healthy again.

I made a discovery when I was writing *Reaching Home*. We were going to put a list of restoration groups in the back of the book. But we found there were too many. It would have taken pages and pages and pages to list all the different community groups that are trying to restore salmon. It's not a class thing—it's not the poor people, or the sports fishermen. It's a cross-cultural phenomenon. There are bankers, there are out-of-work tree planters. The people that are working in restoration, the thing they share is a fierce character. They're devoted to salmon. They've made a kind of ethical commitment. This is a phenomenon, I think, that's part of that "putting the clutch in." All over, people are appearing who love their neighborhoods.

This is a picture of some Canadians cleaning a stream up around Vancouver.

This is a picture of some volunteers putting a weir in Chimacum Creek to catch chum salmon, to try to take their eggs and restore the run.

This slide shows a little restoration hatchery that I'll talk more about later. This is on Salmon Creek in Discovery Bay. The work is very diverse. In our community, where this photo was taken, you'll find a cattle watering trough invented by Kerry Perkins—we call it the Perkins Trough. It's a wonderful little invention that keeps cattle out of the creek. It used to be that whenever the fisheries would dump hatchery fish in the creek, we could always tell, because this little trough would be loaded up with hatchery salmon. You could sit there and watch. The wild fish would squirt through like they were running across a New York intersection. But the hatchery salmon thought this was home. And of course, then, there would always be a heron at this end, and a heron at that end. I've gone down there and watched it. There was a kind of deep irony about it.

One of the lovely things that's happening with restoration is that a craft of restoration is being born. Some of the structures people are learning how to build are actually beautiful. This little ladder was built to help fish pass into that culvert. I go there now as a place for meditation because it's just purely beautiful the way the logs were done. It was all done by boat builders and local construction people, so it has a level of craft that's really quite marvelous. This is something, I think, that is another part of that paradigm shift: focusing our skill and attention on something outside of ourselves.

In conclusion, I thought I would read to you about this little hatchery, because an amazing thing happened there.

> In the early 1990s, our local salmon restoration group undertook a stock rehabilitation project to rebuild the summer chum runs on two east Olympic Peninsula streams—Salmon and Chimacum Creeks. In September, fisheries agents trap chum spawners in a weir, and take a percentage of the eggs. These eggs are eyed up at the Heard Creek hatchery in nearby Sequim, and then turned over to us to incubate in a small hatchery we built on a tributary of Salmon Creek.
>
> By protecting the eggs, we can boost the egg-to-fry survival by almost 100 percent, and hopefully build up the run. We watch the eggs until they hatch, and then feed the fry to a certain size, and release them for their sojourn in the sea. Five volunteers alternate checking eggs and fry daily from November until late April. We are committed to this project for at least 10 years. We hope to rebuild the Salmon Creek stock first, and then transfer Salmon Creek fish to the Chum, Bear, and Chimacum system.
>
> One clear January day, I was at our little homemade hatchery, checking water temperature and flow, alert for the early hatch that sometimes occurs in a warm winter. I lifted the lid on the incubation barrel to check on the 46,000 eggs, the progeny of 20 wild chum hens, supported by black screen trays, and vibrating and rolling delicately in the smooth rhythmic shade of the

waterflow. It is always a little spooky, peering into this watery womb, and I leaned down to study the eggs' opalescent glow. I was trying to decipher what the subtle changes in egg color meant. I was wondering at the dark sentient density of their eyes.

These eggs can see. And that day, I had the uncanny sensation that two eggs in particular were watching me. They followed my motions, rolling and twisting to see me. It was unnerving. As I closed the incubator lid and began to write up the daily report, I had the eerie intuition that those eggs were the eyes of the watershed, venerable and rejuvenant in the same moment. It was as if 8,000 years of watershed experience, the bio-logic, the patient wisdom of Salmon Creek, were coiled in those two vigilant eggs.

That's kind of a romantic view of it—although that really happened, and it really made my life a different life. But I think we can get into a kind of restoration romance. One of the things we know for sure is the salmon know what they're doing. I can imagine a time 3,000 years from now when salmon will be spawning in the rubble of the Kingdome. If we just back out of their way, they know what to do.

So, what about putting the clutch in? Are we all willing to become vernacular Aarons, each with our staff, each taking what we know about the natural world back into our neighborhoods—and building culture, building culture that an economy can nest in, in the way that an egg nests in a real nest, so that it's harmonious, and it's not burning the nest to hatch the eggs?

I wanted to read you one last thing that might provide an image for that.

Imagine a Thanksgiving dinner of your great-great-grandchildren a hundred years from now. In the center of the table is a bright, silver salmon, locally caught, and cooked in the practiced way of long enjoyment and reverence. At the end of the feast, there will be a simple ceremony: a long walk to the creek with neighboring families, each with a wooden bowl of salmon bones, to return the remains to the waters of their creation in gratitude and respect. Perhaps there will be mention of the ancestors, if that is who we decide to be—the old ones, who stayed put, who gave the salmon shelter in their hearts, and who found their own way home.

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DO NATURAL RESOURCE AGENCIES LEARN FROM EXPERIENCE?

Dr. Ray Hilborn
University of Washington School of Fisheries

What I'm hoping to do is describe to you some of the ideas and lessons I've learned in the last eight years—I should mention, largely funded by Washington Sea Grant; thank you, Sea Grant Program—looking at how different institutions learn. I've been dealing mostly with fisheries. And as I looked through the program of the meeting I discovered that there was a fair number of fisheries people represented, a lot of land use, biology and planning. But there really weren't any economics or legal professionals, and as we all know, those are the guys who are really important and run things.

But since they're not here, I thought I might take advantage of their absence to tell you a few of my favorite stories about economists. An economist is a man who's good with numbers but didn't have enough personality to become an accountant. (How many economists do we have here?) An economist is a man who's studied a thousand ways to make love but has never been alone with a woman.

Let me start by describing a situation I was in about 10 or 12 years ago. I was at a meeting of government and industry, something that's getting to be very common now. There was a long table. There were 15 government people on one side and 15 industry people on the other side. In this case, the industry people were commercial fishermen in British Columbia, and the government side was from the Canadian Department of Fisheries and Oceans. I was acting as an advisor for the commercial fishermen at that time.

The leader of the delegation of fishermen was Jack Nichol, who's the president of the United Fishermen and Allied Workers Union in British Columbia, or he was at the time. He listened to the government guys go on for 15 minutes about what they were going to do with this fishery, which I think was the chum fishery in the Johnson Straits. And then Jack Nichol, a fiery orator who came up in the great tradition of unionists, got up and started pounding on the table. He pointed at then-Director of Canadian Fisheries in the Pacific Wayne Shinners, and he said, "You guys are running this fishery by trial and error!"

And a hush fell over the room. The guys in the government didn't know how to respond. What could be worse than running a fishery by trial and error? I got up and did sort of a feeble imitation of Jack Nichol, pounded on the table a few times, and I said, "I only wish it were true." Because although they were clearly making a lot of errors, they weren't learning by it. Lots of things had been tried; lots of things hadn't worked. Some actually had worked, but when you really looked at how the government guys functioned, they didn't seem to pay any attention to the outcome. That really prompted my interest in asking, why is it that institutions seem to have so much trouble learning?

So let's think a little about what trial and error actually consists of. After all, there really isn't an alternative—trial and error is the only way anyone ever learns. The key to successful trial and error is in actually learning from what didn't work and what did work, and in learning from what others have tried. This way you don't have to repeat everybody's mistakes over and over again. Wisdom is, really, not making the mistakes again. The people who aren't doing very well are the ones who keep doing the same wrong thing over and over again.

The first component of trial and error is you've got to know what's actually happened in the past. You've got to know what your agency did. That may seem obvious, but it's remarkable how quickly institutions forget what happened 10 or 15 or 20 years ago, what things were tried. And in many cases, there's no documentation of what actually happened. I've dealt a lot with salmon fisheries, and when I've tried to go back and ask how these fisheries were run, I've discovered there's not much paper on it. In fact, when I ask a student to read on how salmon fisheries are managed, I know perhaps three published papers that describe how salmon fisheries are managed. It's simply not a topic that's documented. And I suspect that when it comes to water quality and things like that, the documentation isn't very good, either. Yet in order to learn, you have to have documentation.

The next component of trial-and-error learning is evaluation. You actually have to go out and say, well, we instituted these regulations; what actually happened? Evaluation is very expensive. Much more commonly than not, it simply doesn't happen.

The last component—and what in theory would seem to be the easiest— is, having documented and evaluated, you actually have to pay attention to the results. As I go through some examples, I'll highlight why the institutional tendency is to not take these critical steps.

Now, there is an alternative to trial and error. I'll use trial and error generically, meaning, try different things, see what works and what doesn't work, and then be more likely to do the things that worked than the things that didn't work. The alternative is what I call blind faith. Blind faith is simply taking your best current knowledge and going with it, and not bothering to evaluate it. Now, it seems like a stupid idea, the idea of doing something and then never really going back and asking if it works. But it's not necessarily bad. In many cases, it's very difficult, if not impossible, to evaluate certain things. In other cases, it may take so long to evaluate them that by the time you've done so, the story will already be over. Or it may be that your knowledge is so precise, there's really no point in evaluating it.

But I think in general—particularly in natural resource issues—there are very few issues where we have that kind of knowledge. We can always learn from the past. So the only real question is, is it really worth evaluation? I've seen a lot of cases where people argue it simply costs too much. And that may be a very real problem. But we need to look into the matter and see how much it would really cost to evaluate something.

One of the key issues here is whether you have controls. Whenever you institute a new policy, the question is always, what would have happened if I *hadn't* instituted the policy? I'm going to talk about the issue of controls a bit later on. But I want you to think about that in light of natural resource management issues: What are the controls on an agency's actions?

Let me first describe a sort of a personal taxonomy of four kinds of learning. I'll start at the bottom, what I call *catatonic learning*. That is where you don't get any learning at all. It's where you have some person, organization, or institution, and no matter how many times they get hit on the head, they never catch on. I've been tempted to classify a lot of institutions that way, but I think it's actually pretty rare. Usually, most places move up to what I call *reactive learning*; that is, they eventually figure it out. They don't intentionally evaluate, but if they do something often enough, the signals start filtering down, and all of a sudden they realize, hey, maybe this isn't working.

The key distinction is that there's really no planned evaluation, no planned response. It's just going along until something happens—the signals filter in, somebody else tells you to do something, then you react to it. And I would say that's really the dominant method in most societal institutions. It's fire fighting. It's waiting for somebody to tell you there's a problem and then responding to it. Institutions that rely on reactive learning are always playing catch-up, always trying to react to a problem that came out of nowhere, a problem they had no built-in mechanisms for detecting.

In contrast to reactive learning, you have what I call *passive learning*. In passive learning, you actually have a system for measuring the response. You have rules about what you'll measure and how you'll respond to it. The classic example I deal with is a large proportion of fisheries stock assessments, or things like in-season salmon management. There, they've got a standardized method of what they're going to measure—they're going to measure escapements; they're going to measure in-season catches. They've got an objective—they're trying to reach certain escapement targets, and they adjust things back and forth to try to do that. I'd say that's a reasonably sophisticated system. They usually get surprised by things they hadn't counted on, but they recognize that they've got a detection system out there to see what's going on. They know the kind of data they're going to collect, and they know how to respond to it. In some of the places—places like Bristol Bay in Alaska—it's very institutionalized. Where the institutions are simpler, its a very well-defined system that seems to work quite well.

The most sophisticated type of learning is what nowadays is often called *adaptive learning*. That is where you're not passively monitoring the system but actively experimenting with it. In adaptive management or adaptive learning, you identify what the uncertainties are; you plan management actions in

an experimental way to determine the differences, to try to resolve the uncertainties; and then you respond to those.

I was part of a group at the University of British Columbia in the 1970s that started using this term in relation to environmental management, and it got to be—and in fact, still is—in some sense, a bandwagon. Particularly in the early '80s in Washington and Oregon, there were a number of disciples of adaptive management, and they sold it to a number of large institutions, such as the Northwest Power Planning Council—which actually inscribed adaptive management as a principle in its fish and wildlife plan. The Timber, Fish & Wildlife Program in Washington state adopted adaptive management as a formal plan.

As Sheri mentioned in the introduction, one of the things I've been doing in the time I've been at UW is asking, OK, they said they were going to do it; are they really doing it? The answer is that, to a great extent, adaptive management has become what people want it to be. Very few places are actually doing adaptive management in the sense of deliberate experimentation, evaluation, and response. But there are some good examples.

Let me talk about one of the problems we face. Probably all of us here would classify ourselves as being in the business of natural resource management. Are natural systems fundamentally amenable to being studied scientifically? Natural systems are very tricky, after all. They're quite a bit different from chemical systems or physical systems. And certainly, learning about them is more difficult than a learning about a lot of other subjects. Think about the key elements of scientific method—and I don't really tend to distinguish between the scientific method and methods for learning, because I think they're almost the same. In science, the big four elements are replication, control, randomization, and blind/double blind experimentation. Those are the hallmarks of good science. Things are replicated, things are controlled, treatments are assigned randomly, and the people involved in the experiments don't know which treatment they're in.

Let me just talk about some of the difficulties of applying these techniques in natural systems. Replication is extremely difficult in a lot of natural resource systems. Sometimes we're dealing with unique resources; you know, there is only one blue whale population in the southern ocean; there's only one Puget Sound. So to have replicates in the sense that a chemist can have replicates is particularly difficult. And, in fact, if you took a basic chemistry and statistics class, you all know that if you want to have the best experimental design, what's the optimum sample size? As much as you can afford, right?

The variance goes down as the square root of the sample size. Bigger sample sizes are always better. Well, the problem in natural resource systems is that even if you do have replicates—even if you've got 10,000 lakes in Minnesota, no two lakes are ever alike—and the bigger your sample size, the more internally heterogeneous it is. In fact, from the point of view of optimum sample size, it's usually a small number rather than a large one. So we can't have infinite replicates, and we're often lucky to have *any* replicates. What's more, very few environmental studies are replicated in the sense that somebody else does them later. If it take 15 years to do a study, the chances are somebody's not going to say, "Oh, that was an interesting result. I think I'll do the same thing for my 15 years."

Control is another very important issue. If you apply a treatment, then do you have a control? This is one of the things I want to stress over and over again. One of the problems we have in our whole institutional structure is we tend to apply rules and regulations uniformly across the country. Nothing could be worse in terms of learning. If you want to learn, you want to have different regulations in different places to see what happens. Often, the laws are written so that you can't, say, allow one county to do one thing, and the next county to do another, in order to learn. Much of the uniformity we impose in regulatory structure is counter to what we need in order to learn how the systems respond.

One of my favorite examples about the need for replication, and about what separates natural resource systems from a lot of other systems, is the example of cold fusion that hit the newspapers three or four years ago. A lot of you probably remember when these two electrochemists announced they had achieved fusion by putting a palladium wire in heavy water and running electricity through it. If true, this was going to mean, potentially, very cheap electricity and all sorts of wonderful things. Immediately, within weeks, there were dozens of labs around the country—in fact, hundreds, I believe—doing the same thing.

And, in fact, within the first couple of weeks they were getting many confirmations of yes, we seem to be getting excess heat, excess hydrogen, or neutrons.

But over the course of about three months, with at least dozens of places replicating this experiment, the truth came out that no one else could really replicate it. Whatever these two electrochemists found, it wasn't as originally advertised. There's still a hard core of people working on the problem, and there may be something going on there. But it's certainly not fusion, and it's certainly not going to give us cheap power in the near future.

The key there was that dozens or hundreds of people repeated that experiment within a matter of weeks. Now if you're thinking in environmental terms, think how many cold fusions may be out there—situations where somebody tried something, it appeared to work once, and people are now doing it without evaluating it, or else it's never even been repeated. Our problems are so expensive to experiment with, and our experiments take so long, I suspect that if we were to make a list of the great natural resource policies, a lot of them would be phonies, but they simply haven't been exposed because we haven't had a chance to replicate them.

Another issue is controls. Natural resources are particularly difficult to control, simply because in natural resources we can't line up test tubes the way some other disciplines can. One of my favorite examples of this problem is the original work that was done on lake fertilization, which took place back in the 1960s. Some limnologists wanted to see what would happen to an oligotrophic lake if they dumped a bunch of fertilizer in it. It took place in Vancouver Island, British Columbia. A group of three limnologists went out in a boat with barrels of fertilizer and started dumping the stuff into Great Central Lake.

Sure enough, they increased the primary productivity and the zooplankton. Then, somewhat to their surprise, four years later, this enormous run of sockeye salmon came back. What had happened was that the increased zooplankton population had led to increased growth of the juvenile sockeye salmon, and their ocean survival went from being not very good to being really good, and the run of sockeye salmon went from tens of thousands to a million in about four years. That's fine, but as good scientists, what would you like to have had? A control, right? Now, there's obviously only one Great Central Lake, but there was another lake nearby called Sprout Lake. Sure enough, these guys, being trained as scientists, used that as a control. What that meant is they simply monitored Sprout Lake at the same time but didn't dump fertilizer in it.

The problem is that the sockeye population in Sprout Lake went up enormously during the same period. It didn't go up as much as it did in Great Central Lake—about half as much. But as most of you probably learned in your 300-level statistics course, if you have a treatment and a control, and they both respond, what do you conclude? You were taught to conclude that the effect was due to environmental change or some uncontrolled change, and that the treatment didn't have an effect. Now what do you suppose happened in Canada? They concluded they had a really good method for producing salmon, and they then went out and treated about 30 lakes the same way and spent tens of millions of dollars on it.

I want to tell you, it was the right thing to do. Why was it the right thing to do? It was the right thing to do because the statistical data were ambiguous—you'd had a big response in the area they hadn't treated. Furthermore, it was very cheap. And if it produced fish the way it appeared to produce fish, the technique was very valuable. You don't want statistics to override common sense, O.K.? If you can go out and, for a couple hundred thousand dollars a year, produce a million sockeye salmon, then go ahead and try it a lot of other places.

That illustrates one of the problems in science: The controls are never perfect; they're always ambiguous. And there's a big difference between science and management. As scientists, you may have been taught that if you treat the experiment and not the control, and you see a response in both, you say there was no effect. But for managers, that's not the right criterion. Managers have to look at the alternative hypotheses and weigh their costs and benefits.

What the data suggested was that there may be a fertilization effect; there may not be a fertilization effect. And it certainly was worth putting a lot more money into it, not on an experimental basis, but on

an applied basis. They just went out and started dumping fertilizer in a lot of places. And the story seems to be that it works sometimes; it doesn't work others. The treatment is nowhere near as effective as it appeared from the first experiment. But there's something there, and I think in British Columbia now they're fertilizing five lakes on a sustained basis. And in Alaska I believe they're fertilizing four or five or six, as well.

One of the problems in the absence of controls is that you try something and things get better; you assume that what you did works. This leads to another form of learning, which I don't put in my standard taxonomy, that I call *superstitious learning*. And that is—I tried it; things got better; it must be right. The classic example in the literature was some experiments performed by B.F. Skinner in his classic Skinner boxes with pigeons. What he did was to give pigeons food pellets for doing things he wanted them to do. But in one experiment (I think this was probably a graduate student's nightmare) he said, let's just give them pellets randomly. So they put 10 pigeons in these boxes and gave them pellets at random times. They'd do this for an hour a day. At the end of, say, a week of training, they found the first pigeon sitting there with its head bent between its legs; and another pigeon had one arm up and one twisted around. Each pigeon had adopted some bizarre form of behavior. It's because they happened to be exhibiting that behavior when the pellet came the first time, so they said, well, I'll try it again. And maybe it didn't set the first time. But after a week or so of similar experiences with the random pellets, the pigeons said, this is it.

Now, think about agencies. Think about why they do things they do. My favorite analogy is sports fishermen. Every sports fisherman I know has some magic. It may be a certain sandwich he brings for lunch. I know one guy who always baits his hook with the left hand. Another guy always pees off one side of the boat. Everybody has these bizarre behaviors. We all know that they're just superstition. But because they seem to work, and because the fishermen do them every trip now, they don't bother to do replicated and controlled experiments. That's just the facts of life.

I mentioned the difference between management and science, and I want to just take a quick snipe at the way we teach people statistics. I was at a meeting earlier in the week on coded wire tags for salmon hatcheries. A fellow was talking about testing various feeds. He was wanting to know whether the other food he'd been using appeared to be giving somewhat better survival. But actually, the main emphasis of the talk was on the power of being able to detect it. He said, oh, you've got to have at least a 50 percent improvement in survival before you can detect it. And his listeners said, what alpha level should I be using? Should I use P=.01, P=.05? The statistician who was giving the paper said, well, it's hard to say. At this point I sort of lost it. I said, look, it's a stupid question to ask. If this feed is cheaper, use it.

Natural resource management issues are questions of decisions in costs and benefits. They're not questions of hypothesis-testing at P=.01 and P=.05 level. There's a whole different kind of statistics—the kind they teach in business schools—that we should actually be using in resource management.

Let me just talk about a few other issues here. One is, why don't we know what happened? That has to do with institutional memory. It's frightening how much information is lost by institutions. Bill Ricker, who's probably the most famous living fisheries scientist now—certainly the most cited, I know that—once said at a meeting that at the laboratory where he worked at he was convinced that information was being lost faster than it was being gained. And the reason was that most of the information was in the filing cabinets in the brains of people he knew, and there was a large cohort of people retiring from his laboratory at the time. So you'd be sending a guy out the door with 35 years of experience and files that would never be used again, and you were bringing in a new scientist who was just starting out.

And I'm convinced that's an accurate assessment. This hit home a couple of years ago when I was trying to get a bunch of data on hatchery releases. I found an old report from the late 1970s on hatchery releases that was a computer print-out, page after page of hatchery-by-hatchery releases. I thought, great, I'll get this. So I phoned the agency. But they said, oh, those were on CDC tapes, and we can't read those anymore. So I had to pay to have this report keypunched again. If that thing hadn't existed on paper, it would have been lost.

I saw an article in a computer magazine recently. It had a picture of the Rosetta stone and a CD-ROM, and it said the Rosetta stone was read 1800 years after its creation. Will this CD-ROM be readable 1800 years from now? The answer's probably no. I don't how many of you have piles of disks and files from Apple IIs or CDCs or some other kind of computer that simply are difficult, if not impossible, to read. These files have life expectancy of a decade or two before the information's physically lost. There's a real concern that we lose information because it's in people's minds and it's in reports that are disappearing. Institutional memory is probably the most important issue. How can institutions retain what they've learned? I'll talk a little bit about what we can do about that, at the very end.

But there are some other impediments to learning. One of them is—and it's intrinsic to natural resource systems—they actually change. What you learn in the 1930s and '40s about a certain ecological response may actually change over time, over certain levels—for example, the relationship between fishing pressure and stock size. Those kinds of things change as the environment changes. It's a problem that bedevils a lot of natural resource issues.

Another major impediment to learning is a thing that's been labeled "goal displacement." You start off with a perfectly legitimate objective. The paper this term was first used in concerned the Mediterranean fruit fly in California. The state had an outbreak of Mediterranean fruit fly and wanted to eradicate it. So they started spraying. Every year they kept having outbreaks, but the California Department of Agriculture said, oh, we're being successful, and they pointed to how many acres they sprayed. That was their measure of success: the more they sprayed, the more successful they were.

Three years ago, hatchery managers in the Columbia River were still being paid bonuses based on how many juvenile fish they let go from the hatchery. The bonuses had nothing to do with how many survived. The measure of success was how many juvenile fish they produced. And, in fact, it's very clear in a lot of places that what matters is the hatchery's mere existence. It doesn't matter if it's producing any fish. In fact, the state of Oregon has been trying to shut down a couple of hatcheries that don't produce any fish, but the local residents say, no, no, you can't do that, it's important to us. The goal is no longer producing fish; it's the action in itself.

So why is it that we don't learn? Let me just recap these things. Lack of institutional memory: we don't know what happened. Lack of controls: that is, we do an action, but we do it everywhere, so we don't have a control to see what *would* have happened. A lack of evaluation: either we never evaluate it, or what happens quite commonly is the evaluation is done by the people who were doing it, and you get a lot of self-justification. If it's a really important project, you almost have to have external evaluation. And then you get goal displacement: that is, you sort of lose track of what you're all about. And particularly in agencies, if you have something that's a big part of your budget, it doesn't really matter if it's working, as long as the money keeps coming in. And that's certainly my critique of hatchery programs—that most of the state fisheries agencies get a substantial portion of their budget from hatcheries. They're not going to say, oh, these things aren't working. Let's shed half our budget.

Now, what can be done? There are four things. One is *institutional history*. I think that every institution ought to have a historian, Newt Gingrich and his recent troubles notwithstanding. It would be very useful to keep track of what happened. And when people are retiring, I would suggest you give them a couple of months to write a very brief synopsis of what they think they learned in the course of their time in the agency. In fact, you might give everybody two days a year to say, did I learn anything this year? What was it? Make these one page. Nobody reads 300-page reports. People would read one or two pages.

Controls on actions. Consciously plan to do things differently in different places. You never know what's right. Try one regulation one place, one regulation another place. Have some control.

Evaluation. When a new program is being planned, build evaluation into it. If there's a lot of agency money involved in maintaining the program, have the evaluation done by someone outside the agency. *Keep program objectives clear*. On an iterative cycle say, O.K., what are we really trying to achieve with this program? What's our real goal? How are we doing it? Have we gotten to the stage where simply doing it has become our objective?

THE PUGET SOUND AMBIENT MONITORING PROGRAM: WHAT HAVE WE LEARNED AFTER FIVE YEARS?

Chris Prescott[1]

ABSTRACT

The Puget Sound Ambient Monitoring Program (PSAMP) is the main body through which Washington state coordinates monitoring and addresses the environmental quality of Puget Sound. The PSAMP is a comprehensive, long-term monitoring program structured as a cooperative effort involving one federal and six state agencies in monitoring eight major ecological components of Puget Sound. The goals and design of the PSAMP are described in the program's design document, and have been presented a ta pervious research conference.

The information gathered by the program over the last five years tells us a great deal about environmental conditions in Puget Sound. Each paper in this session will address some of the major findings of each PSAMP task. In addition, a number of presentations on more focused technical issues are distributes throughout of other sessions. In combining and translating these results into information that is useable by the public, resource managers, and others, the program's findings have been grouped into five key issues affecting the quality of Puget Sound: **chemical contamination** of sediments and marine biota; **fecal contamination** of marine waters, fresh waters and shellfish; **nearshore habitat composition and coverage** in Puget Sound; **abundance of biological resources** within Puget Sound; and **convention water quality** of fresh and marine waters. In addition to the specific PSAMP findings presented in this and other sessions, some overall patterns in the environmental quality of Puget Sound will be discussed.

The five years of data provide not only a baseline for assessing conditions in Puget Sound, but also an invaluable body of data for rigorously evaluating the effectiveness of the monitoring design. The PSAMP is beginning its fifth-year program review, which was built into the original design of the program. The review will evaluate the goals of the program, the effectiveness of its strategy and design in meeting those goals, and recent advances in methodology or understanding that support revision of the original goals or approaches. During the review, program participants and external experts will critically evaluate all aspects of the program—from data collection to reporting—in order to maximize the cost-effectiveness and scientific merit of the program, and to ensure that it reflects current advances in the field of monitoring. The research, coordination, and evaluation that went into creating the PSAMP produced a program that is used as a model by monitoring programs throughout the country. In reevaluating the program to reflect the current state of knowledge, we hope to maintain that stature.

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THE MARINE SEDIMENT MONITORING TASK OF THE PUGET SOUND AMBIENT MONITORING PROGRAM: AN OVERVIEW

Roberto J. Llansó[1]

ABSTRACT

The Marine Benthic Monitoring Unit of the Washington State Department of Ecology has conducted the Marine Sediment Monitoring Task (MSMT) of the Puget Sound Ambient Monitoring Program since 1989. Components of this project include annual monitoring of 188 physical and chemical sediment parameters, sediment toxicity testing (amphipod bioassay), and the enumeration and identification of the benthic infaunal community.

Of the more than 41,000 chemistry values (organic, metal and physical data) collected from 1989 through 1993, greater than 70 percent were undetected and reported at the detection limits. Most MSMT stations are located away from major sources of anthropogenic contamination. The majority of the organic compounds that were detected were qualified as estimates and had values close to the detection limits. Organic compounds were detected more frequently at stations closer to major urban areas and known sources of contamination. Concentrations of organic compounds at most stations were low compared to the Sediment Quality Standards. Metals were much more readily detected than organic compounds. Metal concentrations at most stations were low compared to the Sediment Quality Standards. Amphipod bioassay results failed to clearly indicate toxicity at any station when the effects of sediment grain size are considered. Benthic infaunal analyses indicated heterogeneity in community structure throughout the Puget Sound.

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THE MARINE WATER COLUMN TASK OF THE PUGET SOUND AMBIENT MONITORING PROGRAM

J.A. Newton, S.L. Albertson, L.B. Eisner, and A.L. Thomson[1]

INTRODUCTION

The Marine Water Monitoring Unit of the Washington Department of Ecology has conducted long-term monitoring of Washington state marine waters, including Puget Sound, Grays Harbor and Willapa Bay, since 1973. Since 1989, the monitoring conducted within Puget Sound has formed the marine water column component of the Puget Sound Ambient Monitoring Program (PSAMP).

The overall goals of Ecology's marine water monitoring are:

1) to characterize spatial and temporal patterns of ambient marine water quality in Puget Sound and the coastal estuaries;
2) to identify significant changes in water quality that may indicate environmental changes or emerging problems; and
3) to provide and maintain a long-term water quality database to serve the public and to support researchers and other agencies.

Specific objectives to be achieved in order to fulfill these goals are:

1) to identify water quality-sensitive areas and areas where further study is needed to assess water quality;
2) to distinguish water quality effects due to natural processes (e.g., sluggish circulation) from those of anthropogenic origin (e.g., sewage input); and
3) to determine effective monitoring procedures in order to reveal water quality spatial and temporal patterns.

MONITORING DESIGN: PARAMETERS AND STRATEGIES

Water quality refers to a description of the physical, chemical and biological condition of the water. The distinction between good and poor water quality involves governmental policy and values. Water quality is measured using a wide variety of physical, chemical and biological indicators, as shown in Table 1. The significance of these measurements and their coverage by Ecology is presented in this section.

Measurements of physical parameters of the water column are important because they define the environmental condition and its stability. Because of the fluid nature of the marine environment, the physical attributes at a particular depth in the water column are subject to change. In addition, sinking or swimming organisms will likely see a variety of conditions, so it is important to define what conditions exist where. The physical environment is primarily defined by the water density (temperature, salinity), water stability (mixing, currents), and light intensity. Currently, Ecology measures all of the conventional physical parameters except currents (Table 1). Currents are important because they define residence times and the flushing characteristics of a marine system.

The chemical constituents of sea water are primarily dissolved ions or gases, but also include colloids, suspended particles and adsorbed molecules. Sea water constituents relevant to water quality are shown in Table 1. Nutrients and dissolved oxygen (DO) are involved with biological production, but their concentration also can be affected by anthropogenic influences, such as nutrient or organic loadings. Most metals and a variety of organic molecules are present in trace amounts in sea water, yet industrial and non-point contributions can elevate their concentrations to levels unhealthy for organisms. In addition, many pesticides or other compounds not naturally found in sea water can be added from point and non-point sources.

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Although these contaminants are important, metals and organics have not been measured in the water column by Ecology. This is because they are usually found in trace amounts in the water column, and typically when contamination occurs the molecules primarily adsorb onto particles and sink. Also, many of these analyses are very expensive. Currently, only DO, nitrate+nitrite, nitrite, ammonium, and ortho-phosphate are measured by Ecology. Other chemical constituents could be very important to water quality and not enough is known about their distribution in the marine environment, especially in Puget Sound.

The main biological components of the water column are planktonic forms, including phytoplankton, bacteria, and zooplankton. Information on the ecology of the water column is obtained by measuring these organisms' abundance (or biomass), production and species composition. The abundance of an organism or a group of organisms represents the net balance between growth and death and therefore indicates their degree of success in that environment. Production refers to the population growth rate; it is the product of how many organisms are growing and their individual growth rate. A highly productive population could have low abundance if loss rates were high. Species composition yields much information. Some species can be harmful, such as certain species of phytoplankton that are toxic to humans or other organisms. Some species can be related to anthropogenic impacts, such as fecal coliform bacteria that have originated from human or domestic animal wastes. Lastly, species composition and species diversity can indicate water column characteristics. Blooms of low-salinity-adapted phytoplankton, for example, indicate freshwater input, and low species diversity indicates unstable conditions.

Table 1. Marine water column parameters relevant to water quality monitoring. Parameters marked by "X" are routinely monitored at most stations occupied in the baseline component of Ecology's marine water monitoring; those marked by "x" are measured only at a few selected stations or in focused projects.

Parameter		Monitored by Ecology
physical:		
temperature		X
salinity		X
density		X
current direction and velocity		
euphotic zone depth		X
light transmission		X
chemical:		
nutrients		
nitrate+nitrite		X
	nitrite	x
ammonium		X
ortho-phosphate		X
silicate		
dissolved oxygen		X
pH		X
metals		
organics		
biological:		
phytoplankton biomass		X
phytoplankton species		x
phytoplankton production		x
zooplankton biomass, species & production		
bacterial biomass & production		
fecal coliform bacteria		X

Monitoring of the biological components of the water column by Ecology has focused mainly on phytoplankton. Phytoplankton are important to monitor because these organisms are at the base of the food web

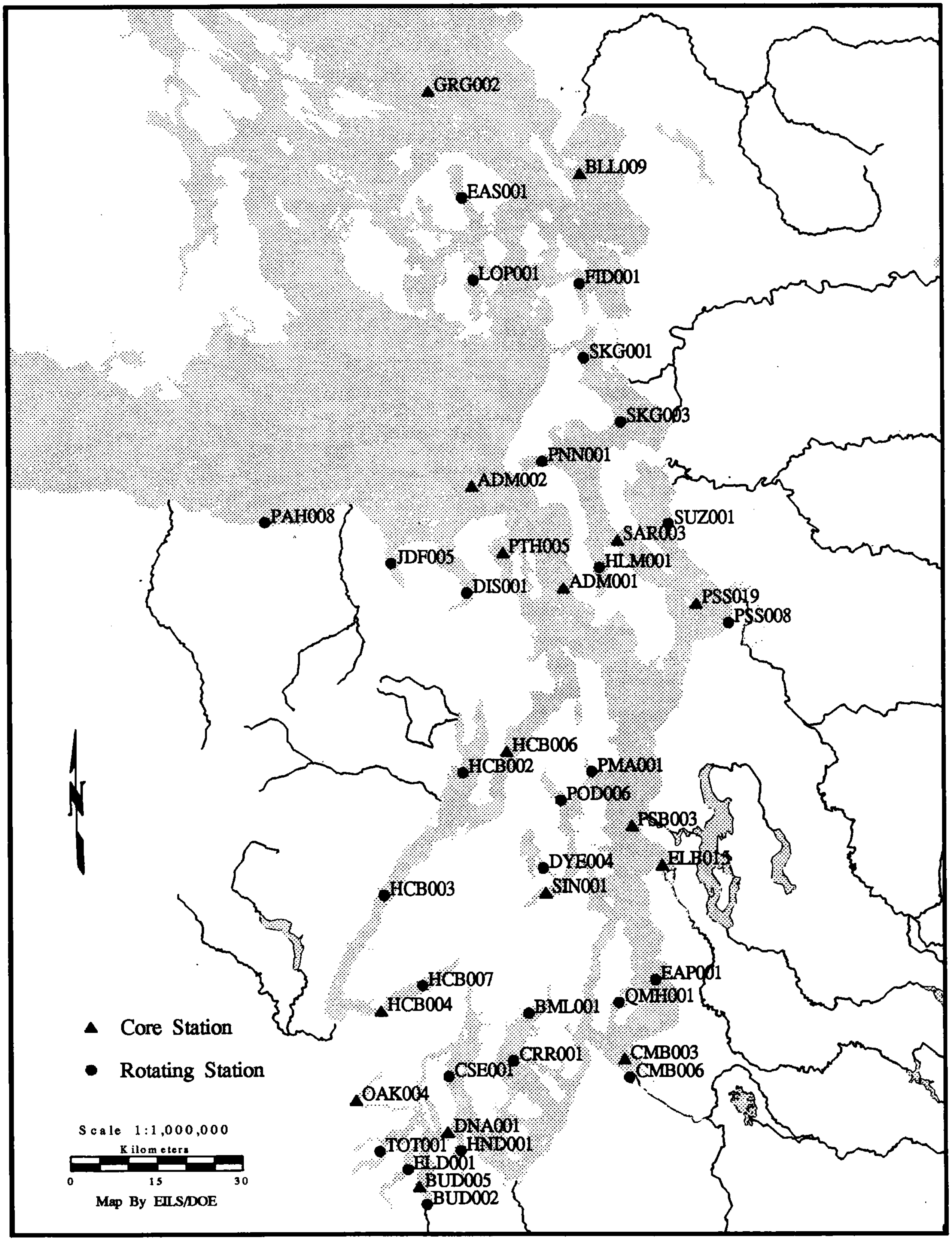

Figure 1. Long-term stations for the Washington Department of Ecology's Marine Water Monitoring

Table 3. Water quality conditions in Puget Sound. Shown are areas where either high fecal coliform bacterial counts (>14 organisms/mL) or low dissolved oxygen (DO) concentrations (<5 mg/L) were measured during WY 1993. Also indicated is the degree of persistent stratification for these stations. Refer to Figure 1 for station locations; data is from station location only, except where a small "x" indicates that data from additional stations in the area recorded low DO, although the long-term monitoring station did not.

Station	Persistent stratification	High fecal count	Low DO
Admiralty Inlet	seasonal		X
Bellingham Bay	X	X	
Budd Inlet	X	X	x
Commencement Bay	X	X	
Elliott Bay	X	X	
East Sound	X		X
C. Hood Canal	X		X
S. Hood Canal	X		X
Oakland Bay	episodic	X	
Possession Sound	X	X	X
Saratoga Passage	X		X
Sinclair Inlet	X	X	x

Other areas in Puget Sound (e.g., Admiralty Inlet) exhibit low DO concentrations at times; however, this condition is natural, caused by the inflow of upwelled deep Pacific Ocean water that has a lower DO signature, and is well-documented in historical data (Collias et al., 1974). The complexity of naturally caused as well as human-stimulated low DO concentrations in Puget Sound makes assessment difficult. Only in areas with adequate historical time-series data can conclusions be drawn regarding long-term changes and impacts. This reality underscores the importance of maintaining long-term monitoring programs. Another difficulty with assessing the extent of low DO problems is that low concentrations are often found in localized or shallower areas but not at the long-term monitoring station (e.g., Figure 1). This result was observed in Ecology data from focused projects in Sinclair Inlet and Sequim Bay, where in each multiple stations (15-18) were monitored as well as the long-term station. These observations underscore the importance of conducting focused projects in concert with long-term baseline monitoring.

3) Since the Marine Water Monitoring Unit is beginning to establish long data records of physical, chemical and biological parameters, it is becoming possible to examine how physical attributes determine biological populations in local waters. Phytoplankton species abundance, composition and diversity were compared in three physically diverse areas in Puget Sound by Eisner (1995). Observed patterns in these parameters often were related to the physical-chemical environment. For example, *Skeletonema costatum*, a diatom that can tolerate brackish water and fluctuating salinity (Spies and Parsons, 1985; Rijstenbil, 1988), was often dominant at a Strait of Georgia station when advection of Fraser River plume waters resulted in periods of lower salinity (<25 PSU). In Budd Inlet, the relative abundance of dinoflagellates to diatoms was high during summer and corresponded with water column stratification and decreased surface nutrient concentrations. Dinoflagellates may outcompete diatoms during such physical-chemical conditions because some dinoflagellate species are capable of migrating vertically at night to deeper waters with higher nutrient concentrations.

Better understanding of relations such as these in local waters is important, not only for predicting events, such as blooms of harmful phytoplankton species, but also for understanding long-term changes. Variations in local climate are reflected in the temperature and salinity of Puget Sound surface waters (Newton, 1995). Reductions in zooplankton populations observed off the California coast have been hypothesized to be correlated with sea temperature shifts (Roemmich and McGowan, 1995). These types of changes have far-reaching implications and provide justification for why understanding the coupling of physical-biological processes is important.

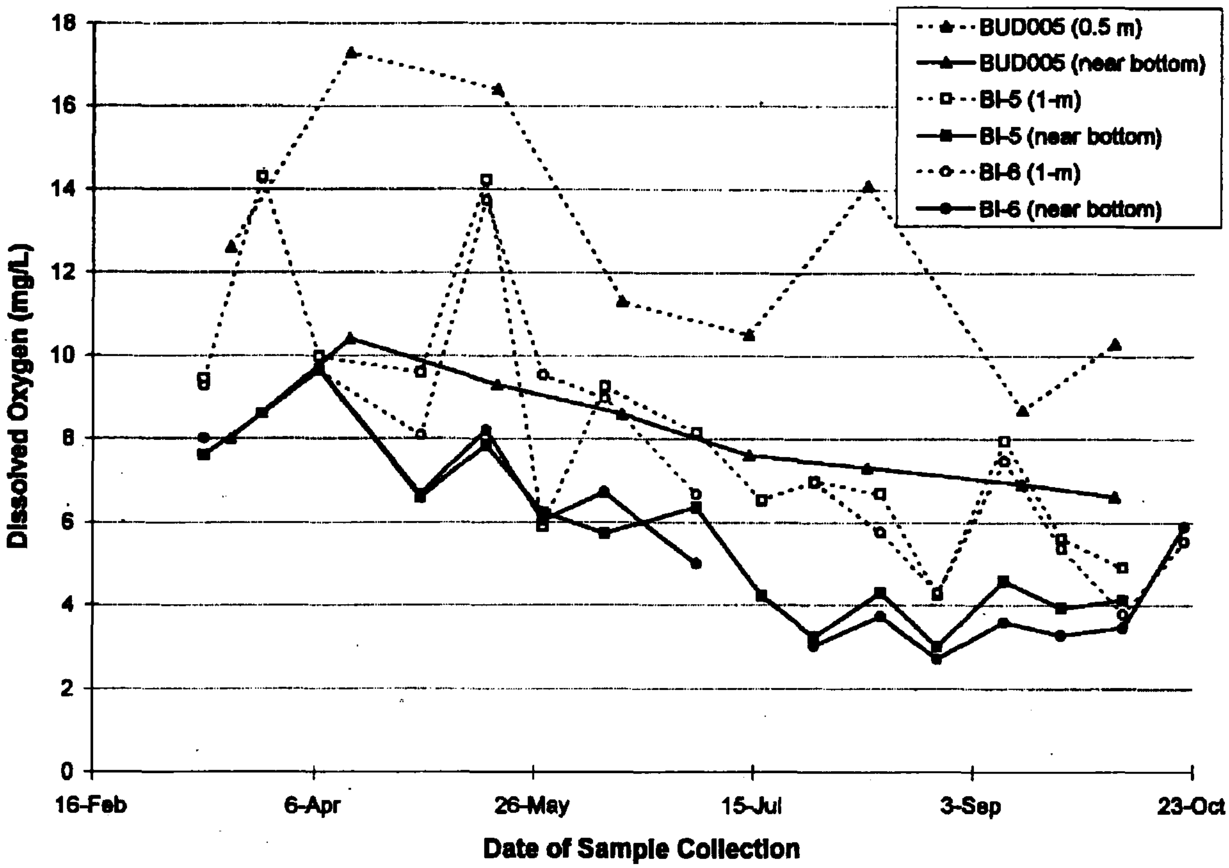

Figure 2. Spatial variation of dissolved oxygen (DO) concentrations in Budd Inlet. One-meter and near-bottom DO concentrations are shown from the long-term station BUD005 as well as focused study stations BI-5 and BI-6 through 1992. Stations BI-5 and BI-6 are located in West Bay in inner Budd Inlet, whereas BUD005 is in the central portion.

4) Another accomplishment of Ecology's Marine Water Monitoring Unit has been to gain information on more effective ways to monitor the marine water column. This is primarily work in progress but includes deployment of sensors to record continuously over long periods (e.g., weeks to months) that allow assessment of day-night variation, the impact of events (e.g., storms, high runoff, etc.), and data from inclement weather conditions that prohibit sampling via seaplane.

   Data collected are also being analyzed using principle component analysis (Albertson, 1995) to assess issues of sampling coverage and factors determining variation. These considerations are important in order to define the most effective monitoring procedures.

DISCUSSION: MONITORING GAPS AND FUTURE DIRECTIONS

Although there have been significant contributions, it is important to consider what is missing from Ecology's marine water monitoring. Two important missing components are water circulation and food-web attributes. Water circulation or the flushing character of Puget Sound is essential information for environmental planning and policy. How long do contaminants stay in Puget Sound? How is this influenced by local climate, runoff, and land-use practices? This research area has been explored by Cokelet and Stewart (1985), Ebbesmeyer et al. (1989), and Cokelet et al. (1991) among others. However, synoptic current meter measurements at key sites throughout Puget Sound have never been conducted. Moored current meters and

sensors at five stations in Puget Sound would add significantly to our ability to answer these questions. These measurements could be used in existing models (e.g., Cokelet et al., 1991) to calculate the flushing of Puget Sound each year.

Food-web measurements need consideration. Do zooplankton stocks in Puget Sound show long-term decline or increase as they do in other areas (cf. Roemmich and McGowan, 1995)? Are contaminants, such as tributyltin, having any effect on planktonic organisms? Can we use organisms or the food-web structure to better indicate water quality? It is important to evaluate how best to obtain this information. The structure of a marine food web is typically complex, is difficult to measure, and can be quite dynamic seasonally. However, it holds much information on water quality, since the organisms are exposed throughout their life cycle to the physical and chemical conditions of the water mass. Planktonic food webs can be characterized and have been used to indicate nutrient availability (e.g., Landry, 1977). A gelatinous zooplankton-chaetognath-small phytoplankton food web indicates fewer nutrients and stable physics whereas a copepod-diatom food web indicates abundant nutrients and mixing. Another approach to monitoring water quality is to deploy test organisms, such as mussels (e.g., Salazar and Salazar, 1991), and measure their growth.

Missing data coverage arises because Ecology currently samples only during daylight, under relatively calm weather conditions and, for the long-term strategy, only once per month. These "snapshots" do not allow an understanding of the system's dynamics or the impact of events. Also, our sampling is conducted during variable tidal stages. This limits the comparative value of the data, especially for identifying seasonal trends, since many parameters (e.g., DO, salinity, chlorophyll) covary with tidal stage at a given station. Moored sensors would facilitate continuous coverage such that dynamics and trends could be better identified.

An environment that is missing from Ecology's marine water monitoring is the surface micro-layer of the water column. Studies have shown different chemical concentrations in this layer than in the rest of the water column (e.g., Word et al., 1987; Cross et al., 1987). The surface micro-layer is an important environment for eggs and larvae; if contamination is significant in this layer, this exposure could be deleterious to those organisms.

Future directions for Ecology's Marine Water Monitoring Unit include three major areas: review and reassessment of current practices; better integration with other PSAMP components; and comparison of the present marine water monitoring data with historical data.

Regarding review, a five-year program review of the PSAMP and its components to be conducted in 1995 will give the opportunity to reassess the present marine water monitoring design. The current monitoring design and the aforementioned considerations will be evaluated internally and by external review.

Regarding integration, the Marine Water Monitoring Unit is placing effort on integrating results and projects with other PSAMP components. A joint project with Ecology's Marine Benthic Monitoring Unit is being conducted to assess low DO concentrations in S. Hood Canal.

Lastly, regarding historical perspective, the Marine Water Monitoring Unit is comparing its present marine water data with historical data. Such a comparison has been the impetus behind the 1994-1995 focused project in Hood Canal on DO concentrations (Newton et al., 1995). In 1995, Ecology's Marine Water Monitoring Unit will conduct a focused project to evaluate the hypothesis that freshwater diversions are changing the salinity character and thus possibly the circulation of basins and estuaries in Puget Sound (Ebbesmeyer and Tangborn, 1995). The focused project will entail transects of salinity measurements in the Whidbey Basin, repeating the stations where data were collected in the 1950s and 1960s by the University of Washington (Collias et al., 1974).

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CONTAMINANT MONITORING IN FISH: OVERVIEW OF THE PUGET SOUND AMBIENT MONITORING PROGRAM FISH TASK

Sandra M. O'Neill, James E. West and Stephen Quinnell[1]

INTRODUCTION

Concerns over declining water quality in Puget Sound, and the potential consequences to fish, wildlife, and humans, resulted in the formation of the Puget Sound Ambient Monitoring Program (PSAMP), a multi-agency effort to assess the environmental health of Puget Sound (Monitoring Management Committee (MMC), 1988). As a participating PSAMP agency, the Washington Department of Fish and Wildlife (WDFW) was charged with implementing the PSAMP Fish Task, a study of contaminant levels in Puget Sound marine fishes. The PSAMP Fish Task is only one component of PSAMP and was designed and implemented (Stern, 1989) and modified (Washington Department Fisheries, 1992) to meet the overall PSAMP goals that were relevant to fish monitoring including: characterizing the condition of Puget Sound, providing a temporal record of changes in key environmental indicators, measuring the success of water quality programs, and supporting research activities (MMC, 1988).

The PSAMP Fish Task objectives are to:

- document current tissue contaminant levels in fish and, where possible, relate these contaminant levels to sediment contamination measured at nearby stations;
- determine the spatial and temporal trends in tissue contamination;
- assess the impact of fish contamination on human health;
- document the prevalence of liver disease in English sole, relating these disorders to fish tissue contamination and sediment contamination measured at nearby stations, and assess the impact of liver disease on fish health; and
- determine the spatial and temporal trends in liver disease for target fish species.

WDFW began the PSAMP Fish Task in 1989 and fully implemented the program in 1991. The PSAMP Fish Task monitors contaminants in six species to give a broad overview of contamination in Puget Sound marine fishes: English sole (*Pleuronectes vetulus*), copper rockfish (*Sebastes caurinus*), quillback rockfish (*S. maliger*), chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*) and Pacific cod (*Gadus macrocephalus*). These species are important to recreational or commercial fisheries and represent a wide range of life histories and feeding patterns. Tissue contamination in these fishes has been monitored as a measure of contaminant accumulation in the marine food web, and the threat to human health from eating fish (MMC, 1988). All contaminant data collected by the PSAMP Fish Task are evaluated by the Washington Department of Health to determine whether consuming Puget Sound marine fishes may be harmful to humans. Prevalence of liver disease is measured as an indicator of the potential impact of contamination on fish health. This paper highlights data synthesis on contaminants in Puget Sound fishes for all data collected from 1989 through 1993 to identify factors correlated with the accumulation of contaminants and so addresses the first objective of PSAMP Fish Task. Where possible, spatial differences are discussed (second PSAMP Fish Task objective). Temporal trends are not discussed as there are insufficient data for statistical analysis. The implications of our results are discussed. More extensive analyses of tissue contaminant data, data on prevalence of liver disease in English sole, and the effect of contamination on fish health will be presented in WDFW (in prep.).

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MATERIAL AND METHODS

Species and Station Locations

English sole were collected with a 400-mesh eastern otter trawl in April and May at 37 stations throughout Puget Sound in 1989 and 1991-1993, the most recent data that have undergone quality assurance review and interpretation (Figure 1). Nine of the 37 stations were "fixed" stations sampled annually. A third of the remaining 28 "rotating" stations were sampled annually so that a rotating station was sampled once in three years (Figure 1). The Department of Ecology (DOE) also collected sediment chemistry samples near most of the English sole stations (Tetra Tech, 1990; Dutch et al., 1993; DOE, 1994; DOE, unpub. data).

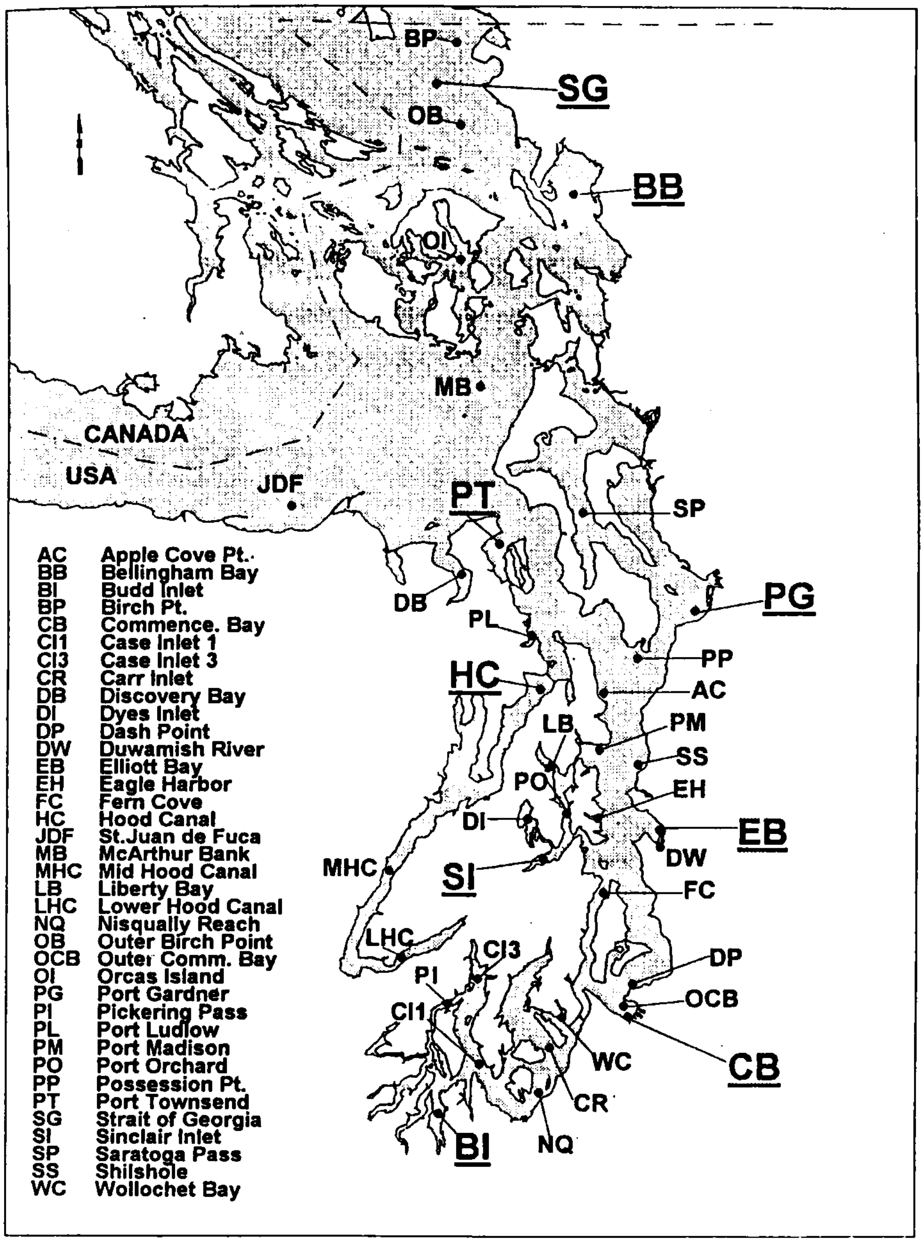

Figure 1. Location of fixed (underlined) and rotating English sole stations sampled by the PSAMP Fish Task from 1989 through 1993

Coho and chinook salmon were caught with a commercial purse seine or purchased from licensed fish buyers and treaty tribal fishermen in the late summer and early fall of 1992 and 1993. Sampling areas included six nearshore marine areas or river mouths where the origins of the fish were presumed ("terminal areas") and three offshore marine areas where the fish origins were unknown ("mixed stock areas," Figure 2). Only three salmon stations, Nooksack River, Skagit River and the Duwamish/Green River, were sampled in both years. Mixed stock areas were not sampled in 1993.

In the fall of 1989 to 1993, quillback and (less frequently) copper rockfish were sampled at five stations using hook and line or by scuba divers with spear guns. Quillback, the targeted species, was consistently sampled at only three stations, San Juan Islands, Double Bluff and Blakely Rock (1991 through 1993). Pacific cod taken as bycatch were purchased from a commercial bottom trawler fishing in the Admiralty Inlet area in March of 1990, 1992 and 1993, and from Alden Bank in 1992 and 1993 (Figure 2).

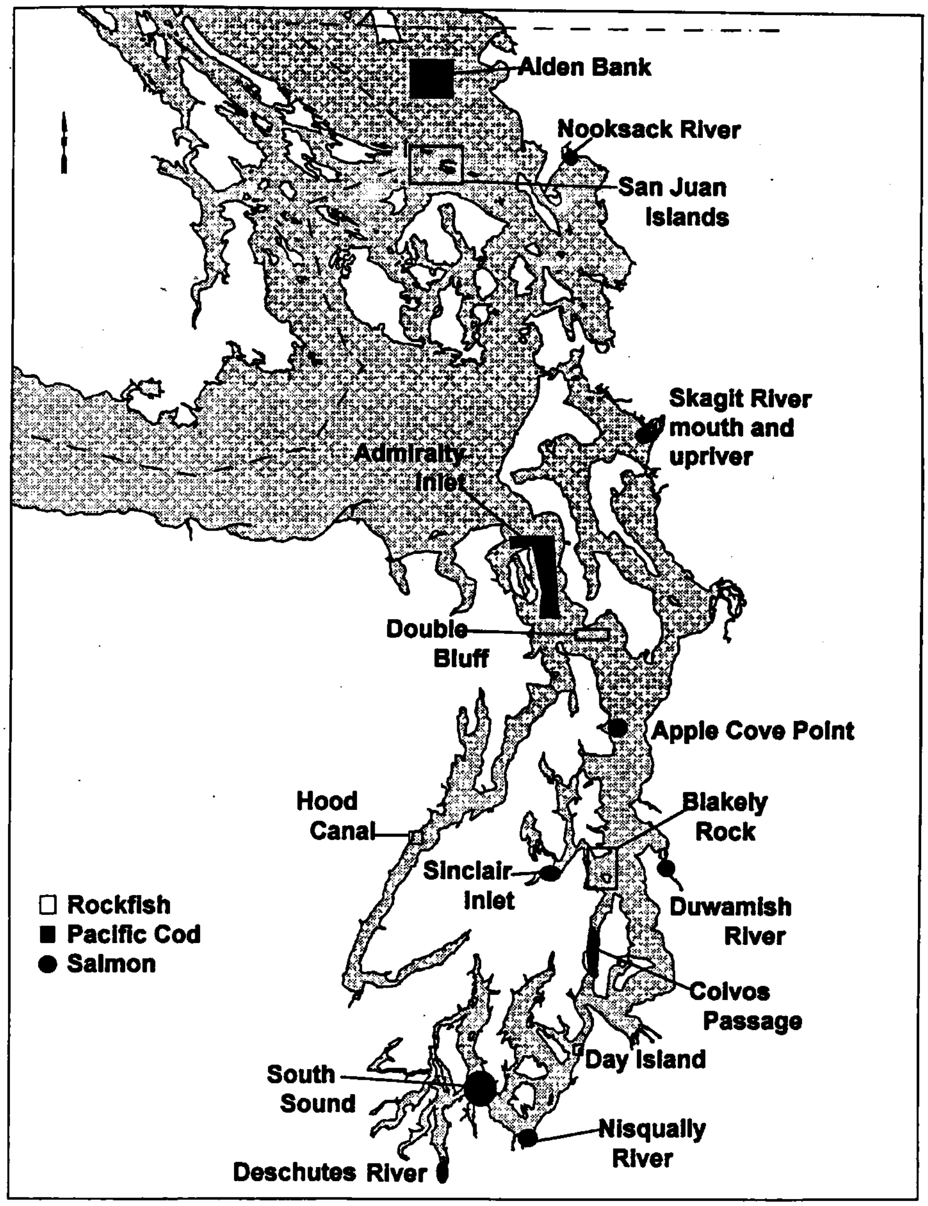

Figure 2. Location of rockfish, Pacific cod and Pacific salmon stations sampled by the PSAMP Fish Task from 1989 through 1993

General Sampling Methodology

On board the boat, English sole were measured (total length), sexed and tagged. Except for 1989, samples of liver tissue were removed and placed in pre-cleaned jars. English sole were then wrapped in aluminum foil, placed in individual zip-lock bags, stored on ice and transferred to the laboratory, where the muscle tissue samples were taken. Rockfish were treated similarly to English sole muscle tissue samples. Purchased salmon and cod were transported on ice to the laboratory and were then tagged, wrapped in aluminum foil, placed in plastic bags and returned to ice until they were processed.

Within 10 days of collection, all fish were weighed and measured (fork length for Pacific salmon and total length for all other species), and the sex was determined. Gill interopercula, otoliths and scales were removed for later age determination of English sole, rockfish, and Pacific salmon, respectively. Pacific cod were not aged. Samples of skinned lateral muscle were placed in pre-cleaned jars. For rockfish, chinook and coho salmon and Pacific cod, muscle tissue samples from five fish were combined to make one composite sample, and usually six composites were collected at each station. Three composite muscle tissue samples were collected at each English sole station, but the number of fish per composite varied among years from five to 20 individuals. Starting in 1991, three composite liver tissue samples were also collected at the English sole stations, but for some stations all three composites were combined if there was insufficient weight of tissue for chemical analysis.

Chemical Analysis

Generally, chemical analyses for organic compounds were conducted according to the Puget Sound Estuary Program's (PSEP) recommended guidelines (1989a). Organic compounds were extracted from fish samples by soxhlet extraction (1989 and 1990) or sonication with a methylene chloride and acetone mix (1991, 1992 and 1993). Starting in 1991, all extracts were "cleaned" with gel permeation chromatography (GPC). Base/neutral/acid (BNA) organic compounds were analyzed by gas chromatography/mass spectroscopy with a DB5-625 column. Pesticides and PCBs were analyzed using gas chromatography and electron capture detection (GC/ECD) with aroclor mixtures used as standards for quantifying PCB concentrations. In 1989 and 1990 a dual megabore column was used on the GC/ECD, but in 1991, 1992 and 1993 a dual narrowbore column (0.25 mm) better suited to analyzing low concentrations was substituted. Starting with the 1992 rockfish samples (fall 1992), new chromatography software was used for quantification of the pesticides and PCBs, allowing laboratory chemists to more accurately quantify low concentrations of pesticides and PCBs.

The laboratory modifications initiated in 1991 and 1992 improved the accuracy and precision of the pesticide and PCB analysis. Consequently, pesticide and PCB data from 1989 and 1990 (all species) and the 1991 rockfish samples were excluded from data analysis in this report. PCB data for the first set of English sole liver samples, collected in 1991, were also excluded from data analysis due to insufficient quality assurance/quality control documentation (e.g., unconfirmed matrix-based detection limits).

Analyses for inorganic elements followed the PSEP recommended guidelines (1989b). Mercury was analyzed by the cold vapor atomic absorption method. Arsenic and copper were extracted using nitric acid/hydrogen peroxide and analyzed by inductively coupled argon plasma spectrophotometry. Lead was analyzed by the graphite furnace atomic absorption method. Arsenic data for all of the 1989 samples were qualified as estimated values and excluded from data analysis. All chemistry data were reported as the concentration per wet weight of tissue.

Data Analyses

Mean age, mean length and mean percent lipids were computed for the fish comprising each composite sample. Hence, all contaminant analyses were conducted using mean composite age (MCA), mean composite length (MCL) and mean composite percent lipids (MCPL).

Detection limits for particular compounds were similar within fish species among years, and detection limit values were used for all non-detected compounds, except as noted below. PCB detection limits varied for the English sole liver samples from 1992 to 1993, and for statistical analyses, the values of all non-

detected arochlors were assumed to be zero. PCB detection limits for the DOE sediment samples also varied among years, and all non-detected arochlors were assumed to be 1 for statistical purposes. Total PCBs were calculated by summing the values of the routinely detected arochlors (1248, 1254 and 1260). Total DDT was calculated by summing the values for 4,4-DDT, 4,4-DDD and 4,4-DDE.

For comparison of fish species, station or year means, data were first assessed for normality, homoscedasticity of variance and quality of residuals. All data met assumptions for parametric analysis, except for minor violations of the homoscedasticity assumption. If necessary, PCB data were log-transformed to linearize data. One-way analysis of variance with Tukey multiple range comparisons (STSC, 1991) was used to identify station location-differences in parametric means.

Linear regression analysis was used to model accumulation of contaminants, with stepwise (forward) variable selection (STSC, 1991). Variables modeled included sediment concentration (English sole only) MCA, MCL, and MCPL. For the rockfish and Pacific salmon data, dummy variables (Kleinbaum and Kupper, 1978) were used to model the accumulation of contaminants due to station effects.

RESULTS

PCBs, DDT metabolites, mercury, arsenic, copper, and lead were the main contaminants detected in Puget Sound fishes. An overview of these results are presented here; more detailed analyses will be presented in WDFW (in prep.). Except for phthalates, benzyl alcohol, and benzoic acid, which were detected intermittently, BNAs were not detected in Puget Sound fishes. These results will also be detailed in WDFW (in prep.).

PCBs

Mean PCB concentration was higher in English sole liver samples than any muscle tissue samples (Table 1). For the muscle samples, the highest PCB concentration was detected in chinook salmon, followed by coho salmon, English sole, quillback rockfish, Pacific cod, and copper rockfish (Table 1). Except for Pacific cod, PCB concentrations within a species varied considerably among some station locations. PCBs were never detected in Pacific cod from Alden Bank and were detected in only two of 12 Admiralty Inlet samples at 18.7 and 15.6 ug/kg, values near the detection limit (15 ug/kg).

PCBs were present in most muscle tissue samples of English sole, with individual composite concentrations ranging from 6.9 ug/kg (the limit of detection) in fish from non-urban areas (e.g., Birch Bay, Hood Canal and Discovery Bay) to 159 ug/kg in fish from the very urbanized Duwamish Waterway (Table 1). The highest mean concentration of PCBs was detected in fish from the Duwamish Waterway (110 ug/kg) followed by Sinclair Inlet (54 ug/kg), Elliott Bay (49 ug/kg), and Commencement Bay (44 ug/kg). At the fixed stations with multiple years of data, PCB concentration in English sole muscle tissue were significantly higher in fish from urbanized areas (Sinclair Inlet, Elliott Bay and Commencement Bay) than non-urbanized areas (ANOVA on logged [PCB], $p<0.0001$, d.f.=8; Figure 3). Stepwise linear regression testing the relative effects of fish age, fish length, percent lipids, and sediment PCB concentration indicated that sediment PCBs accounted for 39 percent of the variation observed at the fixed stations, and fish age accounted for 6 percent ($p<0.001$).

All chinook salmon samples and most (55 of 66) coho samples had detectable concentrations of PCBs with concentrations in individual composites ranging from 11.5 to 216 ug/kg for chinook and 4.7 (the detection limit) to 107 ug/kg for coho (Table 1). Mean concentrations of total PCBs were higher for chinook (50 ug/kg) and coho (27 ug/kg) than English sole muscle tissue (20 ug/kg; Table 1) but were lower than in English sole liver tissue (546 ug/kg; Table 1). Percent lipid values were also lower in salmon samples than in English sole liver samples (Table 1).

Overall, PCBs were detected at higher mean concentrations in salmon from mixed stock areas than terminal areas, but the concentrations detected in Puget Sound salmon were approximately 10 times lower than mean concentration detected in salmon collected from Lake Michigan (Figure 4). Chinook and coho collected in mixed stock areas had higher percent lipids (4.3 percent and 2.1 percent) than chinook and coho in terminal areas (2.6 percent and 2.05 percent). Based on skin coloration, fish in terminal areas were closer to

Table 1. Summary of contaminant data for Puget Sound marine fish sampled by PSAMP Fish Task, 1989 - 1993. Results are grand mean values for Mean Composite % Lipid (MCPL), Mean Composite Lenght (MCL), Mean Composite Age (MCA), trace metals, PCBs, and DDT.

Species		MCPL	MCL	MCA	Arsenic (mg/kg)	Copper (mg/kg)	Lead (mg/kg)	Mercury (mg/kg)	PCB (ug/kg)	DDT (ug/kg)
English sole (muscle)	Mean	0.32	286.63	5.54	8.26	0.31	0.03	0.06	19.67	4.41
	Std	0.16	34.42	1.92	3.08	0.27	0.01	0.02	21.91	0.77
	Max	0.87	392.00	10.40	20.00	3.60	0.11	0.14	159.00	9.40
	Min	0.09	214.00	2.00	2.90	0.14	0.03	0.02	6.00	3.90
	N	96	192	192	162	192	192	177	161	161
English sole (liver)	Mean	4.16	288.78	5.63	9.43	7.27	0.56	0.09	546.21	12.50
	Std	0.89	31.00	1.86	7.65	2.94	0.58	0.04	1173.75	34.12
	Max	6.30	365.40	9.80	48.00	14.00	3.50	0.23	7100.00	250.00
	Min	2.60	235.60	2.20	2.00	2.60	0.06	0.04	0.00	0.00
	N	27	102	102	77	77	77	77	68	62
Chinook (muscle)	Mean	2.95	749.33	3.62	1.05	0.49	0.03	0.10	49.98	22.17
	Std	3.61	82.03	0.56	0.31	0.07	0.00	0.03	37.36	11.17
	Max	22.20	898.60	5.00	1.80	0.65	0.04	0.16	216.00	58.80
	Min	0.24	530.00	2.00	0.60	0.32	0.02	0.06	11.50	6.27
	N	66	66	66	66	66	66	66	66	66
Coho (muscle)	Mean	2.07	534.08	2.99	0.75	0.50	0.03	0.05	26.67	10.10
	Std	1.53	49.09	0.04	0.24	0.08	0.00	0.02	19.90	3.47
	Max	8.95	604.40	3.00	1.60	0.84	0.04	0.11	107.00	18.50
	Min	0.20	402.00	2.80	0.40	0.40	0.02	0.03	4.70	3.80
	N	66	66	66	66	66	66	66	66	66
Quillback rockfish (muscle)	Mean	0.41	314.04	12.72	2.41	0.25	0.03	0.22	11.44	1.68
	Std	0.33	38.04	6.07	1.11	0.12	0.01	0.11	11.63	1.02
	Max	2.29	410.00	32.40	6.60	1.10	0.09	0.51	69.00	6.50
	Min	0.17	247.20	5.40	1.00	0.10	0.02	0.06	4.00	1.00
	N	38	67	67	61	67	67	67	38	38
Copper rockfish (muscle)	Mean	0.43	316.95	5.37	2.16	0.23	0.03	0.11	9.23	1.47
	Std	0.20	44.05	2.05	0.69	0.04	0.01	0.05	2.47	0.27
	Max	0.79	398.00	12.20	4.80	0.30	0.09	0.30	16.00	2.00
	Min	0.21	234.00	3.20	1.50	0.13	0.02	0.04	6.60	1.30
	N	12	28	28	20	25	28	28	12	12
Pacific cod (muscle)	Mean	0.11	517.95		3.83	0.24	0.03	0.11	11.08	3.10
	Std	0.13	47.89		1.85	0.04	0.00	0.03	4.43	0.92
	Max	0.49	628.00		8.80	0.33	0.03	0.18	18.70	4.00
	Min	0.01	450.00		1.30	0.20	0.02	0.06	6.60	2.20
	N	22	29		24	26	29	29	24	24

spawning. At all sampling areas, PCB concentrations were consistently higher in chinook than coho salmon (Figure 4).

Chinook salmon had a higher mean PCB concentration than coho salmon, and were generally older and had higher percent lipids (Table 1). Data for the Nooksack River, Skagit River and the Duwamish River (the only terminal stations sampled in both years of the study) were further analyzed to determine the factors associated with bioaccumulation of PCBs. At these stations, PCB tissue concentration was positively correlated with percent lipids. However, chinook salmon had higher concentrations of PCBs than coho salmon, even after accounting for differences in lipid content (Figure 5).

Variation in percent lipids explained 35 percent of the variation in PCB concentration observed in chinook salmon from the Nisqually, Skagit, and Duwamish rivers (stepwise linear regression; $p<0.0001$). Chinook PCB concentration was not correlated with length, age or site location. Similarly, PCB concentra-

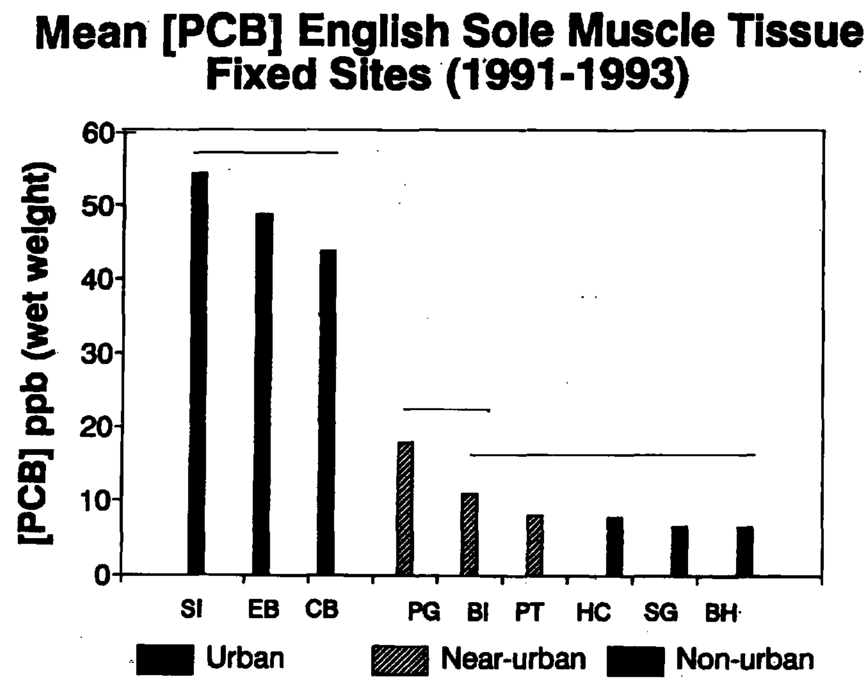

Figure 3. Mean PCB concentrations (ug/kg wet weight) detected in English sole sampled by the PSAMP Fish Task at fixed stations from 1989 through 1993. Horizontal lines indicate means that were not significantly different from each other.

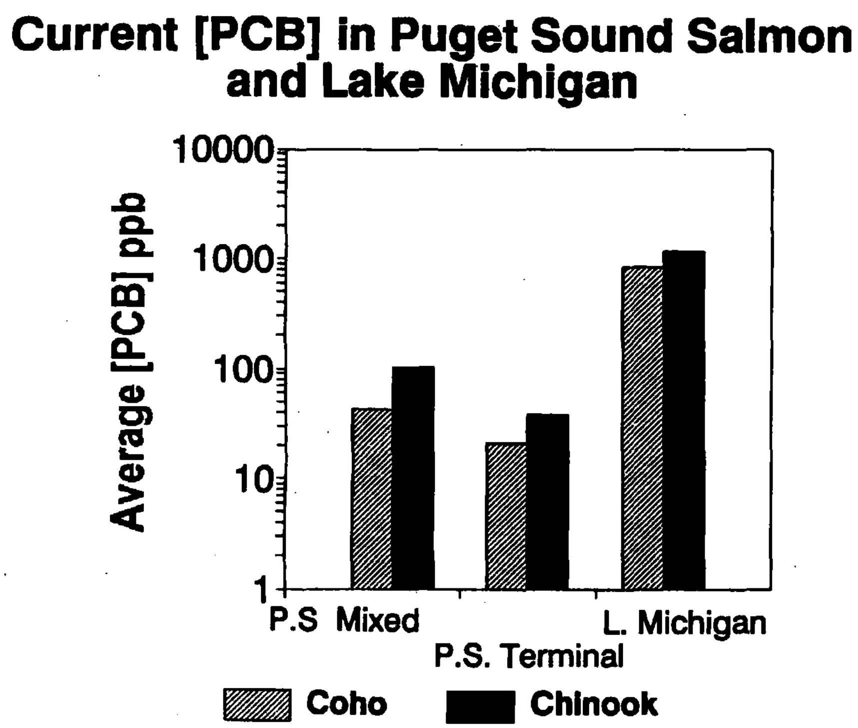

Figure 4. Mean PCB concentrations (ug/kg wet weight) detected in chinook and coho salmon from mixed stock and terminal areas of Puget Sound (sampled by PSAMP Fish Task from 1989 through 1993) and Lake Michigan (Stow et al., 1994)

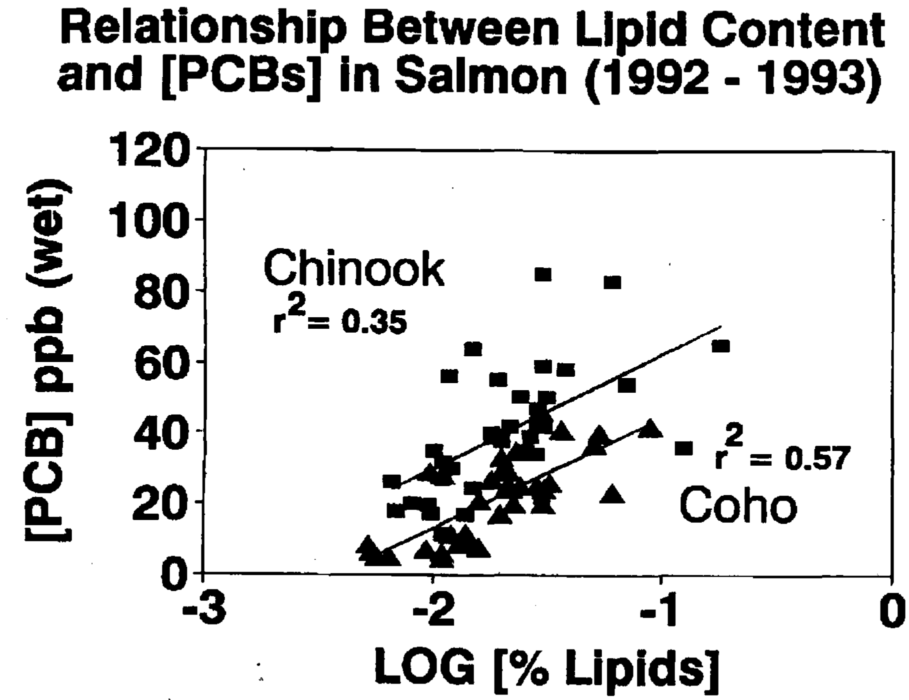

Figure 5. Relationship between lipid content and PCB concentration (ug/kg wet weight) in chinook and coho salmon sampled in Puget Sound by the PSAMP Fish Task from 1989 through 1993

tion in coho was mostly correlated with percent lipids but, unlike chinook, the Duwamish River had a significantly higher PCB concentration ($p<0.00001$) than the other stations. Together, percent lipids and site location explained 68 percent of the observed variation in coho PCB concentration at the Nisqually, Skagit and Duwamish rivers.

PCBs were detected in all the copper rockfish samples and 36 out of 38 of the quillback rockfish samples; composite concentrations ranged from 6 to 16 ug/kg and 4 to 69 ug/kg, respectively. Data from Blakely Rock, the San Juan Islands and Double Bluff were further analyzed by West and O'Neill (this volume) to identify factors correlated with the bioaccumulation of PCBs in quillbacks. Briefly, those results indicated that PCB concentration (as aroclor 1260) was positively correlated with fish age, and station location (stepwise linear regression; $p<0.0001$). Age contributed significantly to within station variation; older fish contained higher contaminant loads. However, Blakely Island samples had a higher PCB concentration than expected based on fish age.

DDT

Mean DDT concentration in muscle tissue was higher in chinook (22 ug/kg) than coho (10 ug/kg) salmon and was seldom detected or was detected only at very low levels in the other fish species (Table 1). DDT concentrations in individual composite samples ranged from 6.3 to 58.8 ug/kg for chinook and from 3.8 to 18.5 ug/kg for coho salmon.

Like PCBs, DDT concentrations in chinook and coho were positively correlated with lipid content. Variation in percent lipids explained 33 percent of the variation in DDT concentration among the samples from the Nisqually, Skagit and the Duwamish rivers (stepwise linear regression; $p<0.0002$). For coho, percent lipids and fish length together accounted for 45 percent of the variation in PCB concentrations at these

sites. Mean DDT concentrations in English sole liver samples were comparable to values detected in coho salmon (Table 1).

Mercury

Mean mercury concentration was highest in quillback rockfish, followed by Pacific cod, copper rockfish, chinook salmon, English sole livers, English sole muscle and coho salmon (Table 1). Mercury concentrations in composite samples ranged from 0.06 to 0.51 mg/kg for quillback and 0.04 to 0.30 mg/kg for copper rockfish. Data from Blakely Rock, the San Juan Islands and Double Bluff were further analyzed by West and O'Neill (this volume). Briefly, those results indicated that a length and age interaction (presumably representative of growth rate) was the primary determinant of mercury concentration in quillback rockfish, accounting for 76 percent of the variation (stepwise linear regression; $p<0.001$).

Mercury was present in all English sole muscle and liver samples with a slightly higher mean concentration in the liver samples (Table 1). Stepwise linear regression analysis indicated that mercury concentration in liver tissue was positively correlated with the fish age, which accounted for 66 percent of the variation, and with the concentration of mercury in the associated sediments, which accounted for 14 percent of the variation ($p<0.001$).

Mercury was detected in all Pacific cod samples ranging from 0.06 to 0.18 mg/kg (Table 1). Fish length, which is correlated with Pacific cod age, was positively correlated with mercury concentration (O'Neill, 1995; WDFW, in prep).

Mercury concentrations in composite samples of chinook and coho salmon ranged from 0.06 to 0.16 mg/kg and 0.03 to 0.11 mg/kg, respectively. Data for the Nooksack, Skagit and Duwamish rivers (the only terminal stations sampled in both years of the study) were further analyzed by stepwise linear regression (WDFW, in prep). At these stations, mercury concentrations in chinook salmon were positively correlated with fish age, accounting for 44 percent of the variation ($p<0.001$). For coho, station location and fish

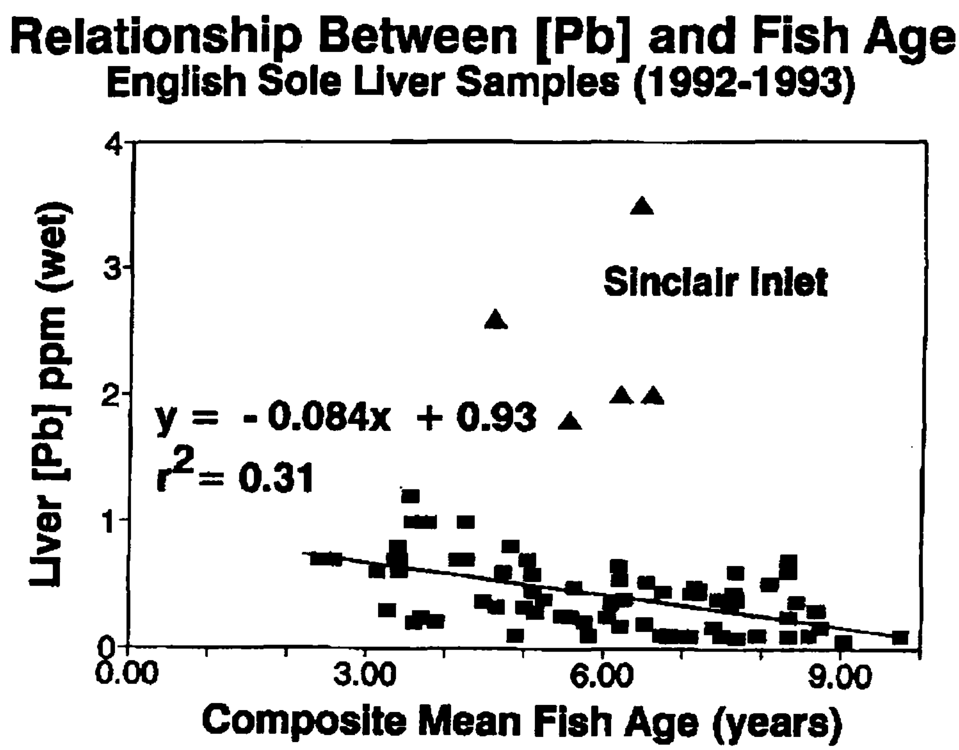

Figure 6. Relationship between fish age and lead concentration (mg/kg wet weight) in English sole liver samples collected by the PSAMP Fish Task from 1989 through 1993. Regression line excludes samples collected at Sinclair Inlet.

length by station location interaction accounted for 43 percent of the variation in mercury concentration ($p<0.001$). Almost all coho from the Nooksack, Skagit and Duwamish rivers were three years old, but the Skagit River coho were larger and had higher mercury concentrations (WDFW, in prep).

Lead

Mean lead concentration was highest in English sole liver samples (Table 1). Lead was never detected in the muscle tissue of the salmon, rockfish or Pacific cod. Very low concentrations of lead, at or near the detection limit (0.03 mg/kg), were consistently detected in English sole muscle samples from Sinclair Inlet but not in English sole from other stations. Excluding data from Sinclair Inlet, stepwise linear regression analysis indicated that lead in English sole liver samples was negatively correlated with fish age (Figure 6). Concentration of lead in nearby sediments was not correlated with lead concentration in English sole liver samples.

Arsenic

Arsenic concentrations were highest in English sole, followed by Pacific cod, rockfish, and salmon (Table 1). However, within a species, factors such as fish age, fish length, percent lipids and site location were not generally correlated with arsenic concentration (WDFW, in prep.).

Copper

Similar copper concentrations were observed in the muscle tissues of English sole, Pacific cod and quillback and copper rockfish (Table 1) and generally did not vary among stations within a species (WDFW, in prep.). Higher copper concentrations were detected in chinook and coho salmon than in the other fish species (Table 1). Copper concentrations in English sole were higher in samples of liver than in muscle tissue, and concentration in either tissue generally was not correlated with sediment copper concentration fish age, fish length or percent lipid (WDFW, in prep.).

DISCUSSION

The purposes of the PSAMP Fish Task were to document contaminant levels in selected fish species from locations throughout Puget Sound and to determine the factors responsible for variation among and within locations. PCBs, DDT metabolites and mercury bioaccumulate in English sole, chinook and coho salmon, and quillback and copper rockfish. Copper and arsenic bioaccumulate in all Puget Sound fishes, but lead seldom accumulates. Except for phthalates, benzyl alcohol and benzoic acid, which were detected intermittently, BNAs were not detected in Puget Sound fishes. In general, we documented contaminant levels comparable to those detected in previous studies. Furthermore, we identified abiotic factors (sediment concentrations of contaminants) and biotic factors (fish age, size at age, and lipid content) that explained much of the variation in levels of these contaminants. An understanding of the factors affecting accumulation of particular contaminants is essential to tracking spatial and temporal changes in contaminant levels in the species monitored by the PSAMP Fish Task.

The ranges of PCBs, DDT metabolites, mercury, lead, arsenic, and copper contaminant concentrations detected in Puget Sound fishes were comparable to or lower than those detected in other Puget Sound studies (Gahler et al., 1982; Malins et al., 1982, 1984; Galvin et al., 1984; Romberg et al., 1984; Tetra Tech, 1985; Landolt et al., 1987; Tetra Tech, 1988; PTI, 1990). PCB levels detected in English sole were similar those reported by Landolt et al. (1987), but English sole sampled in the late 1970s and early 1980s (Malins et al., 1980, 1982) had substantially higher concentrations. The levels of DDT detected in fish in our study were generally lower than those reported in previous studies (Gahler et al., 1982; Galvin et al., 1984; Landolt et al., 1987). This observation is consistent with results reported by Matta et al. (1986) and Mearns et al. (1988), who showed that organochlorine pesticides and their metabolic breakdown products have decreased in fish from Elliott Bay over time.

PCBs

PCBs were used extensively as coolants and frequently mixed with oils and greases in electrical transformers. Although their manufacture has been banned since 1977, PCBs are ubiquitous in aquatic systems (Phillips, 1994) and have been transported to remote polar ecosystems via atmospheric processes (Hammer, 1989). Exposure to PCB-contaminated sediments, coupled with subsequent exposure through the food chain, affects the accumulation of PCBs in fish (Varanasi et al., 1992).

Our results are consistent with other studies showing that proximity to PCB-contaminated sediments, lipid content, fish age and growth rate affect the accumulation of PCBs in fish (Jensen et al., 1982; Masnado, 1987; Larsson et al., 1991; Varanasi et al., 1992, 1993; Hammar et al., 1993; Loizeau and Abarnou, 1994; Stow et al., 1994). In our study, mean PCB concentrations in muscle tissue samples were higher in chinook and coho salmon than all other species and were correlated with biotic factors like lipid content and fish age. After accounting for variation in percent lipids, PCB concentration in chinook salmon did not vary among terminal stations. Furthermore, the total body burdens of PCBs in chinook smolts leaving the contaminated estuary of the Duwamish River (Varanasi et al., 1993) were much lower than in adult chinook salmon returning to the Duwamish River, suggesting that PCBs were accumulated primarily in marine waters of Puget Sound and the north Pacific (WDFW, in prep). Salmon are likely exposed to low concentrations of PCBs in their food, but because of their high lipid content, salmon readily retain these lipophilic contaminants.

Differences in PCB concentration between chinook and coho are likely affected by variation in diet (chinook tend to eat more fish; Beacham, 1986), age (the chinook sampled were older), and life history (coho spend more time in fresh water). Chinook and coho caught in mixed stock areas had higher contaminant levels of PCBs and DDT than conspecifics caught in terminal areas. This probably resulted from the lower lipid content in fish caught in terminal areas, related to the more advanced state of maturation of salmon ascending rivers. PCB concentrations might be even lower in fish caught in up-river terminal fisheries if lipid concentrations were also lower.

Unlike chinook and coho salmon, benthic fish like English sole are closely associated with marine sediments, potentially exposing them to higher contaminant levels. English sole in urbanized embayments are exposed to higher PCB concentrations than salmon, as the liver samples contained much higher PCB concentrations despite having comparable percent lipids. Higher PCB concentrations accumulated in the muscle tissue of English sole associated with PCB contaminated sediments than English sole from uncontaminated areas (Figure 1), but because of their very low lipid content, the concentrations in English sole from urban areas were similar to the mean PCB concentration observed in chinook salmon.

Fish age, especially for long-lived species like rockfish, affected PCB concentration. Although the mean PCB concentration in composite quillback rockfish samples was lower than in chinook, coho, and English sole muscle samples, older individual rockfish could have significantly higher concentration. Future monitoring of individual rockfish, especially older fish, is needed to document maximum concentration of PCBs.

Mercury

We demonstrated that most (66 percent) of the spatial and temporal variation in mercury concentrations in English sole liver tissue was explained by variation in fish age. For chinook salmon we observed higher mercury concentrations in older fish (accounting for 44 percent of the variation). Chinook salmon had higher mercury concentrations than coho salmon, perhaps related to the greater total age, diet and duration of marine residence of chinook salmon. We documented that location-specific growth rates also appear to affect accumulation of mercury in quillback rockfish, and that one of the composite samples had mercury concentrations higher than that recommended for human consumption by the World Health Organization (0.5 mg/kg). Virtually all (95 percent) of the mercury present in fish is mono methyl mercury (Bloom 1993), which is toxic. Thus, within Puget Sound, long-lived fishes like quillback and copper rockfish, lingcod (Ophiodon elongatus) and dogfish (Squalus acanthias) may accumulate very high levels of mercury that is toxic to humans.

Our results are consistent with other studies noting the importance of age or growth rate on the accumulation of mercury in fish tissue (Braune, 1987; Monteiro and Lopes, 1990; Larsson et al., 1991; Monteiro et al., 1991). However, fewer studies have demonstrated that proximity to contaminant sources affect accumulation in fish (Leah et al., 1991). In WDFW (in prep), we also demonstrate that at those stations where the ages of English sole did not vary significantly among stations, proximity to mercury contaminated sediment accounted for 67 percent of the observed variation. English sole are benthic feeders and although they are not as long-lived as quillback rockfish, exposure to mercury contaminated sediments, especially for older individuals, may exacerbate the accumulation of mercury in their tissues.

Lead

Our results are consistent with other studies that have shown that lead generally does not accumulate in skeletal muscle due to the very low binding rate of lead to sulfhydryl groups in the muscle tissue (Sorensen, 1991). Lead is a non-essential element that is absorbed by the epithelium of the fish's gills and intestine and rapidly metabolized in the liver (Sorensen, 1991). We observed higher lead concentrations in English sole liver samples than in muscle tissues. With the exception of English sole from Sinclair Inlet, older English sole had lower lead concentrations in their liver than younger fish, suggesting that older fish can more readily metabolize lead (Figure 6).

In Sinclair Inlet, English sole may be exposed to a higher lead loading because lead is somehow more bioavailable at this site or because the lead concentration in sediments is higher than that indicated by the sediment chemistry samples collected at that station. Exposure to heavily contaminated sediments, like those at Sinclair Inlet, may surpass English sole's ability to regulate the body burden of lead. To further define the extent of lead contamination at Sinclair Inlet, other marine species should be monitored, especially invertebrates, for which trace elements may be more readily bioavailable.

Copper

In general, copper concentrations did not vary greatly among fish species nor among stations within a species and were not correlated with the abiotic and biotic factors we tested. Copper and other essential elements like zinc are actively regulated by fish. Consequently, the tissue concentrations are maintained within specific ranges and do not always reflect environmental levels (Phillips and Rainbow, 1989). The liver actively processes and stores large amounts of copper (Sorensen, 1991) and then transports the required amounts of this elements to muscle tissue and other organs as needed. Only if fish are exposed to excessive copper levels does the regulatory mechanism break down and toxicity occur (Phillips and Rainbow, 1989; Sorensen, 1991).

Arsenic

As with the copper analysis, the abiotic and biotic factors that we tested for were not correlated with arsenic in English sole samples. Mean concentration of arsenic was highest in English sole samples suggesting that bottom-feeding fish, such as English sole, accumulate higher arsenic levels than pelagic fish (LeBlanc and Jackson, 1973; Kennedy, 1976).

Arsenic is ubiquitous in seafood, occurring mainly as an organic penta-valent form that is non-toxic (Edmonds and Francesconi, 1993), suggesting that it is readily accumulated in muscle tissue of marine species and is not usually a health concern. Natural sources of arsenic, including oceanic water, rivers, and shoreline erosion contribute over ten times more arsenic to Puget Sound than do anthropogenic sources (Dexter et al., 1981; Landolt et al., 1987). Crecelius (1985) concluded that arsenic body burden in Puget Sound flatfishes was not related to anthropogenic sources.

SUMMARY AND RECOMMENDATIONS

Our results have demonstrated that various abiotic (proximity to contaminated sediments) and biotic factors (fish age, length, growth rate and % lipids) affect the bioaccumulation of contaminants in English sole, chinook and coho salmon, Pacific cod, and quillback rockfish. By statistically accounting for these various factors (stepwise linear regression), we were able to document spatial differences in the accumulation of

PCBs, mercury and lead. Ongoing monitoring should carefully composite fish of similar size and age, or monitor individuals, so that temporal trends in contaminant levels are easier to detect.

PSAMP was designed to include a full programmatic review every five years, with the first review to take place in the summer and fall of 1995. As part of the review, the PSAMP Fish Task is considering the following recommendations: (1) adding additional species, including important forage fish like Pacific herring (*Clupea harengus* pallasi) that have lipid-rich muscle and roe tissue; (2) monitoring individual rockfish and other long-lived fish such as lingcod and dogfish to determine whether contaminant loadings are a human health concern; and (3) discontinuing monitoring BNAs as they are seldom detected in Puget Sound fishes and considering monitoring other contaminants not currently monitored.

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PUGET SOUND AMBIENT MONITORING PROGRAM—SHELLFISH MONITORING

Bob Woolrich and Glen Patrick[1]

This paper summarizes results of shellfish tissue monitoring from the Puget Sound Ambient Monitoring Program (PSAMP) carried out by the Washington Department of Health's Office of Shellfish Programs. More detailed information is available through the Department of Health.

MONITORING PLAN

From selected beaches in Puget Sound, Health analyzed shellfish tissue for the presence and concentration of: (1) fecal coliform bacteria; (2) paralytic shellfish poison (PSP); and (3) certain organic and inorganic chemicals. Information was gathered to establish baseline concentrations and to measure changes over time. These data are also useful for assessing human health risks associated with shellfish consumption.

Shellfish sampling sites were broadly distributed throughout Puget Sound. Many of the sites selected are used by the public for non-commercial, recreational shellfish harvesting. Some sites located near past or present industrial activities were selected due to the likelihood of elevated chemical or bacteriological contamination. Other sites, isolated from contaminant sources, were expected to provide data on background levels of contaminants.

FECAL COLIFORM CONCENTRATIONS IN SHELLFISH

Methods

The targeted shellfish species was the native littleneck clam (*Protothaca staminea*). Native littleneck clams are one of the most common shellfish species harvested recreationally in Washington.

Native littleneck clams were collected quarterly for fecal coliform concentration determination. A total of 60 clams were collected from each site at low tide. The clams were divided into three size groups: small, medium, and large. The clams were then recombined into two samples of 30 clams each, composed of equal numbers of small, medium, and large clams. This sampling method minimized the differential role that size may play in the concentration of contaminants.

The laboratory procedures used for estimating the concentration of fecal coliform bacteria in shellfish tissue followed the most probable number (MPN) method as defined in "Laboratory Procedures for the Examination of Seawater and Shellfish," Fourth Edition, published by the American Public Health Association.

Fecal Coliform Sites

Twenty-two separate beaches were sampled in 1992 and 1993. Fifteen of those beaches were sampled during each of the eight quarters.

RESULTS AND OBSERVATIONS

1. Results varied significantly at most sites. In 1992-93 eight sites had individual sample results with ranges that covered two or more orders of magnitude, e.g., Walker Park (170-22,000) and Dosewallips State Park (20-3500). Results from Sequim Bay State Park (<20-45) and Camano Island State Park (<20-130) varied less than one order of magnitude. The large range of results at individual sites may be attributed to changes in the number of fecal coliform bacteria in the water column and the variability within the MPN test. There is also evidence to suggest that environmental factors such as water temperature, salinity, and tidal phase may have a great effect on fecal coliform concentrations (Bernard, 1989).
2. For evaluation, fecal coliform results were placed into one of three MPN categories: 30, 31-230, and >230. Generally, shellfish are considered to be uncontaminated when results are less than 30 MPN

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per 100 grams of shellfish tissue. The category of results greater than 230 MPN was selected for the most contaminated category because historically the Shellfish Program has used this level to indicate the need for further testing at the wholesale market level.

3. At most of the sites, the tissue data tends to support Health's shoreline pollution source information. For example, shellfish tissue at Belfair State Park had high levels of fecal coliform bacteria. This was expected because of numerous known failing on-site sewage systems located along the shoreline and in the nearby community of Belfair. At the other extreme, fecal coliform levels in shellfish tissue have been very low at Camano Island State Park, which is isolated from any known pollution source. However, not all the results reflect anticipated pollution levels. For example, samples from Ross Point have typically been low in fecal coliform concentrations despite the fact that two sewage treatment plant outfalls are located in Sinclair Inlet. These results may indicate either that the treatment plants are operating efficiently or that the currents in this bay do not move the bacteria from the sources to the sampling site.
4. Shellfish tissue results varied by season, with fecal coliform levels generally lowest in the winter quarter. This is unexpected because fecal coliform levels in nearshore seawater are typically highest in the winter due to increased stormwater runoff, combined sewer overflows, and wet season failures of on-site sewage systems. The lower tissue numbers in winter are probably related to the impact of cold water temperatures on the physiology of clams. In one study, eastern hardshell clams, *Mercenaria mercenaria*, contained few coliforms when seawater temperatures were below 10C even when growing in heavily polluted waters (Cabelli and Herrernan, 1971). Apparently, the clams' rate of uptake and rate of elimination of bacteria are not equally affected when temperatures are colder.

High fecal coliform concentrations have been found at Dosewallips State Park in the spring. This appears to be related to the resident harbor seals that haul out there during the spring months and leave their waste in the upper intertidal zone (Melvin, Health, personal communication).

With just four years of data, conclusions on the seasonality of fecal coliform levels may be premature. Levels may be related to the circumstances at the time of sample collection, such as the timing of recent rainfall events, water temperature, and salinity. These parameters have not been tracked.

PARALYTIC SHELLFISH POISON (PSP) CONCENTRATIONS

Alexandrium catenella, a naturally occurring photosynthetic dinoflagellate, is responsible for paralytic shellfish poisoning (PSP) in Washington state's marine waters. This organism is usually present in low num-

Table 1. 1992 / 1993 Fecal coliform results In shellfish tissue at selected sites

SITES/ COUNTY	NUMBER OF SAMPLES	RANGE (MPN)	MEDIAN MPN	MPN ≤30	MPN 31-230	MPN >230
Walker Co. Park (Mason)	16	170 - 22,000	2,148	0	2	14
Belfair St. Park (Mason)	16	80 - 7,900	1,359	6	8	2
Dosewallips (Jefferson)	14	20 - 3,500	713	1	5	8
Carkeek Co. Park (King)	16	<20 - 2,300	399	2	7	7
Saltwater St. Park (King)	14	<20 - 2,300	376	5	6	3
Priest Point (Thurston)	16	<20 - 1,700	316	3	9	0
Burton Co. Park (King)	16	<20 - 230	90	6	8	2
Semiahmoo Spit (Whatcom)	16	<20 - 330	87	7	8	1
Ross Point (Kitsap)	16	<20 - 230	79	9	7	0
Frye Cove (Thurston)	16	<20 - 490	72	12	3	1
Jarrell Cove (Mason)	16	<20 - 230	40	14	2	0
Camano Is. St. Pk. (Island)	16	<20 - 130	33	12	4	0
Sequim Bay St. Park (Clallam)	16	<20 - 45	23	14	2	0

bers. During PSP "blooms," filter-feeding shellfish, such as clams, oysters, mussels, and scallops, can accumulate PSP toxin in concentrations that are dangerous, or even fatal, to humans. A 200 mg tablet of crystalline saxitoxin derived from *Alexandrium catenella* can kill 35 people or cause moderate poisoning in 350 people (Brusca and Brusca, 1988).

Because of serious public health implications, the Washington Department of Health routinely monitors PSP levels in both commercial and recreational shellfish areas. Areas are closed to harvest when PSP toxin levels equal or exceed the FDA standard of 80mcg/100g of shellfish tissue.

Several experts believe that PSP has become more prevalent and more severe in Puget Sound in recent years (Taylor, 1994). As of January 1994, the only areas not found to have blooms of PSP-causing alga were south Puget Sound and central and southern Hood Canal. The factors that promote PSP algal blooms are still not well understood; however, El Niño events and the discharge of ship ballast water may have some association.

PSP Methodology

Sixteen sites were selected to track the occurrence and concentration of toxin in tissues. Sites were selected to provide geographic coverage of Puget Sound and the expectation of regular sampling. A variety of species were tracked. Species included Pacific oysters (*Crassostrea gigas*), blue mussels (*Mytelis edulis*), butter clams (*Saxidomus giganteus*), native littleneck clams (*Protothaca staminea*), and Manila clams (*Tapes philippinarum*). PSP testing procedures require 100 grams of shellfish tissue homogenate, i.e. 8-10 oysters or 30-40 littleneck clams.

Shellfish biotoxin concentrations were determined at the Washington Public Health laboratory. All of the shucked shellfish tissue is used for testing. PSP concentration is quantified by a mouse bioassay method using the mouse unit as the unit of measurement (APHA, 1984). The mouse unit is defined as the minimum amount of poison required to kill a mouse weighing 20 grams in 15 minutes when 1.0 ml of shellfish sample extract is injected intraperitoneally. The lowest detection limit for the bioassay is 34 mcg of toxin / 100 grams of tissue; below that level, no further distinction in concentration is possible.

PSP Results—1990 Through 1993

Of the 16 PSAMP PSP sites selected, six sites did not register toxin levels greater than 80 mcg/100 g of tissue in the four years. These included Hamma Hamma in central Hood Canal, Skookum Inlet and Harstene Island Bridge in south Puget Sound, Holmes Harbor and Penn Cove in Island County, and Westcott Bay in San Juan County. The highest level was recorded at Ship Bay in San Juan County in 1991 (1462 mcg). Sites having levels over 500 mcg during 1990-1993 included Edmonds Oil Dock in Snohomish County, Drayton Harbor in Whatcom County, Point Bolin in Kitsap County, Fauntelroy Ferry Dock in King County, and Samish Bay in Skagit County.

At two sites, analysis showed levels of PSP concentration differing markedly by shellfish species. At Point Bolin, butter clams registered toxicity levels over 700 mcg/100 g at the same time that littleneck clams were below the 80 mcg/100 g level. At Drayton Harbor/Semiahmoo Marina, mussels accumulated the toxin before oysters, attained higher levels of contamination (972 mcg/100 g compared to 240 mcg/100g), and were slower to purify than the oysters. These results were not unexpected. The Pacific oyster (*Crassostrea gigas*) is believed to possess an instinctive behavioral response to stop feeding when exposed to certain toxic phytoplankton (Twarog and Yamaguchi, 1981). PSP toxin concentrations in molluscan shellfish may differ by species due to:

- Different species' filtering rates
- Reaction of each species to the presence of the alga
- Species' different toxin retention times (Shumway, 1990)
- Position of the species in the water column
- Position of the species in the harbor or bay

Spatial and seasonal trend conclusions cannot be drawn from the limited data of this study. However, it

appears that PSP blooms are most prevalent in summer and fall. It is also apparent that at some sites low-level wintertime blooms precede the summer-fall blooms.

Future Analysis

In 1990 Health began to develop a mussel collection program to serve as an "early warning system" for biotoxin episodes. In Puget Sound, Health has now established approximately 30 mussel cage sites, stocked with blue mussels (*Mytelis edulis*). The PSP data from these sites will be used in the future for the PSAMP program. A more thorough evaluation of spatial and temporal trends should be possible using this data because only one species is collected and the sites are sampled regularly. The use of mussel data will also more accurately reflect the current level of biotoxins in the water column since blue mussels accumulate and release the toxin more quickly than most other shellfish species.

SHELLFISH CHEMICAL CONTAMINATION

Native littleneck clams were collected from a total of 29 sites for determination of metals, pesticides, base/neutral/acids (BNAs), and polychlorinated biphenyls (PCBs) concentrations. These data were collected to meet PSAMP objectives.

Methods

Native littleneck clams samples were collected from 20 sites in 1992 and 19 sites in 1993, with 10 sites being sampled in both years (see map). Sites were not selected with the intention of targeting point discharges, although sampled sites were generally located near anthropogenic sources of chemical contamination. Such sources included: waste-water outfalls, and past and present shipbuilding, military, and industrial activities. Equal numbers of small, medium and large individuals were combined in composite samples of approximately 30 individuals each. Only unbroken legal-sized native littleneck clams were harvested. Three composite samples were collected from each sample location.

Preparation of shellfish tissue for chemical analyses followed established PSAMP protocols (PSEP, 1989). Target analytes included base/neutral/acid (BNA) extractable organic compounds (phenols, PAHs, semivolatiles, ethers, phthalates, and organonitrogen compounds), pesticides, polychlorinated biphenyls (PCBs), and selected metals (arsenic, cadmium, copper, lead, mercury, and zinc). Analytical procedures outlined in the PSEP protocols were employed in 1992 and 1993 along with the following method improvements intended to achieve greater analytical performance:

- use of high resolution columns for pesticide and PCB analyses;
- use of comprehensive standards for both BNA and pesticide analyses; and
- lower characterization of instrument response for BNAs.

Chemical analyses were conducted by the Municipality of Metropolitan Seattle (METRO) Environmental Laboratory, and all data underwent an independent QA/QC review.

Chemical Results

Fifteen chemicals from the 105 analytes measured were detected in littleneck clam samples.

Six metals (arsenic, cadmium, copper, lead, mercury and zinc), were detected in all composite samples from all locations (Table 1). Concentrations of trace metals in littleneck clams were low, with the exception of zinc, which ranged from 8.4 ppm to 19 ppm. Mean cadmium, copper, lead and mercury concentrations in littleneck clams were similar between years for sites sampled in 1992 and 1993, while mean arsenic and zinc concentrations were slightly elevated in 1993 shellfish samples compared to samples collected in 1992. Mercury concentrations for samples collected in 1993 were reported as estimates with the exception of data from Eagle Harbor.

Nine organic chemicals (2-methylphenol, benzoic acid, benzyl alcohol, bis(2-ethylhexyl)phthalate, butylbenzylphthalate, di-n-butylphthalate, fluoranthene, phenanthrene and pyrene), were detected in littleneck clams during the 1992 and/or 1993 PSAMP shellfish sample collection/analysis effort (Table 3). Organic chemical analytical results varied between years and among samples.

Few organic chemicals were detected in native littleneck clams analyzed for PSAMP. PAHs (fluoranthene, phenanthrene and pyrene) were detected only at concentrations in the low ppb range and only in samples from Eagle Harbor. 2-Methylphenol was detected for the first time in samples collected in 1993. Benzoic acid was the only organic chemical reported in all shellfish samples collected both years. Bis(2-ethylhexyl)phthalate and di-n-butylphthalate were detected in blank control samples resulting in blank correction of littleneck shellfish results. Benzyl alcohol and butylbenzylphthalate were detected only in samples collected in 1992.

A human health screening assessment, based on U.S. EPA reference dose (RFD) and cancer potency values, was conducted for chemicals detected in littleneck clams. Preliminary results indicate that the maximum mean concentration of each chemical, with the exception of lead, is of little human health concern. No conclusions can be drawn for lead since the EPA RFD is currently under review.

CONCLUSIONS ON SHELLFISH CHEMICAL CONTAMINATION

Results from the 1992 and 1993 PSAMP shellfish tissue analytical results indicate that littleneck clams contain trace metals but few organic chemical contaminants. Of the 105 analytes measured, only 15 chemicals were detected in littleneck clams. Maximum mean chemical concentrations were determined to be of little human health concern, with the exception of lead, whose toxicity is currently under review by EPA.

Table 2. Trace metals data summary, native littleneck clam samples collected in 1992 and 1993

(Concentrations reported in mg/kg (ppm) wet weight.)

Metal	n	Concentration (mg/kg) Min.	Max.	Mean	Location of Max. Concentration
Arsenic	115	1.2	3.2	1.9	Manchester
Cadmium	115	0.1	0.39	0.22	Semiahmoo
Copper	115	0.71	3.2	1.2	Eagle Harbor
Lead	115	0.02	1.2	0.12	Eagle Harbor
Mercury	115	0.01	0.08	0.02	Eagle Harbor
Zinc	115	8.4	19	13	Ross Point

n = number of composite samples analyzed.
Each composite sample consisted of 30 individual shellfish.

Table 3. 1992 & 1993 PSAMP native littleneck shellfish detected trace organic chemical summary. (Concentrations reported in ug/kg (ppb) wet weight.)

Chemical	Detection Frequency (a) 1992 (n=58)	Detection Frequency (a) 1993 (N=57)	No. of Sites (b) 1992 (s=20)	No. of Sites (b) 1993 (s=19)	Detected Conc. Min.	Detected Conc. Max.	Location of Max Concentration
2-Methylphenol	0	20	0	9	27	150	Misery Point
Benzoic Acid	57	56	20	19	280	8800	Eagle Harbor
Benzyl Alcohol	5	0	3	0	270	2900	Jarrell Cove
Bis(2-ethylhexyl)ph	5	10	4	8	410	4130	Semiahmoo
Butylbenzylphthalate	19	0	9	0	22	130	Walker Park
Di-n-butylphthalate	14	0	10	0	32	1522	Liberty Bay
Fluoranthene	3	3	1	1	40	170	Eagle Harbor
Phenanthrene	0	3	0	1	28	36	Eagle Harbor
Pyrene	1	3	1	1	22	39	Eagle Harbor

(a) Number of samples in which the chemical was detected. (n) Total number of samples analyzed each year.
Three samples were analyzed from each location each year, with the exception of Picnic Pt. and Sequim Bay in 1992 (2 samples only)
(b) No. of Sites reflects the number of sites where the chemical was detected. (s) Total number of sites sampled each year.

Trace metals (arsenic, cadmium, copper, lead, mercury and zinc) were detected in littleneck shellfish samples from all locations. Mean trace metals concentrations varied little between years and were generally low, with the exception of zinc.

Few organic chemical contaminants were detected (2-methylphenol, benzoic acid, benzyl alcohol, bis(2-ethylhexyl)phthalate, butylbenzylphthalate, di-n-butylphthalate, fluoranthene, phenanthrene and pyrene). Results varied highly for some chemicals between years and among samples.

Eagle Harbor samples were found to contain the greatest number of contaminants, the highest concentrations of copper, lead and mercury, and the only detected concentrations of fluoranthene, phenanthrene and pyrene.

While the current PSAMP shellfish protocols for trace metals analyses seem adequate for determination of metals concentrations, analytical methods for determination of organic chemical contaminants may not be. Variability in organic chemical analytical results and lack of detection of chemicals such as PCBs in these samples suggest that current analytical and data collection methods as well as project objectives should be reviewed.

ACKNOWLEDGMENTS

Many people in DOH and local health departments participated in the field work and lent their technical assistance. Particular thanks go to DOH employees Cathy Barker for coordinating the field work and Denise Garrett for her assistance in preparing the report. Special thanks to Adopt a Beach for assistance in the field sampling, and Dr. David Kalman (University of Washington) for his help with the chemical data interpretation.

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OVERVIEW OF THE MARINE BIRD, WATERFOWL, AND MARINE MAMMAL MONITORING TASK WITHIN THE PUGET SOUND AMBIENT MONITORING PROJECT, JULY 1992 TO MARCH 1994

David R. Nysewander[1]

INTRODUCTION

The Wildlife Management Program of the Washington Department of Fish and Wildlife (WDFW) was given responsibility in 1991 for designing and implementing monitoring plans for marine birds, waterfowl, and marine mammals under the Puget Sound Ambient Monitoring Program (Monitoring Management Committee, 1988). The bird and mammal portions of the Puget Sound Ambient Monitoring Program (PSAMP) were not fully funded until the 1991-93 biennium. Study design for the bird portion of the task along with consolidation of historical databases were contracted November 20, 1991, to Ecological Consulting Inc. (ECI). The present project staff began in mid-May 1992 under the Game Division of the Wildlife Management Program to direct, conduct, and coordinate this task. The final implementation plan was produced in March 1993 (Nysewander et al., 1993), even though surveys and contract field work were begun during the summer of 1992 and the winter of 1992-93.

The Monitoring Management Committee set down the following goals for monitoring of bird resources under PSAMP in 1988: 1) to monitor the abundance of selected avian species to identify any significant changes or trends that may be related to pollution, habitat loss, or disturbance; and 2) to monitor reproductive success and contaminant levels in birds. The latter goal is addressed and implemented by the U.S. Fish and Wildlife Service (USFWS) in a contaminant monitoring plan for birds (Mahaffy, 1994). USFWS also has an ongoing seabird colony monitoring effort in Washington state, operating out of their refuge system, which monitors reproductive success for a certain limited set of species.

The purpose of the marine mammal component of PSAMP was to provide consistent population estimates of the marine mammals living in Puget Sound, and to increase the level of knowledge of toxic body burdens and their effects on marine mammals. The harbor seal (*Phoca vitulina* richardsi) is considered the most appropriate species to first monitor as it is the only common resident marine mammal that breeds in Puget Sound.

Three tasks were performed directly by the Wildlife Management PSAMP staff and some of the results will be a primary focus of this presentation. The tasks were: 1) to perform an aerial survey of the entire marine shoreline of greater Puget Sound in summer and winter; 2) to incorporate this survey data into the database and GIS mapping programs (CAMRIS) set up by the initial study design contract for this program, with the intent of making some beginning efforts to compare the 1992-94 surveys with those found in the historical database created by the same contract; and 3) to compare air and boat surveys conducted in both seasons to begin developing a correction factor for the aerial surveys.

A second group of tasks was performed by some combination of efforts of department PSAMP staff, other department regional or research staff, and federal marine mammal scientists. Results from these will be referred to other reports. These tasks were: 1) to quantify the age ratio observed for juvenile and adult marbled murrelets (*Brachyramphus marmoratus*) in Puget Sound in August; 2) to monitor harbor seal populations by aerial surveys and photography on haul out sites during August-September; and 3) to monitor contaminant levels in harbor seals at certain sites and to monitor any attempts to examine how these may relate to the seals' foraging areas and reproductive success.

A third group of tasks involved contracts with the private sector. These tasks were: 1) to create a synthesized historical database of marine birds and waterfowl from three historical surveys, with the largest amount of data coming from the MESA study conducted in 1978 and 1979 (Wahl and Speich, 1980; Wahl et al., 1981); 2) to survey and evaluate the nature of gray whale use of Puget Sound during spring and summer

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(this work included photographic identification, data archival, and creation of a photographic catalog of summer resident gray whales of the inner marine waters of Washington and British Columbia); and 3) to conduct censuses of winter resident shorebirds utilizing Puget Sound. These results will also either be referred to another report or used for comparison with present ongoing surveys.

METHODS

Continuous Aerial Transects

The use of an on-board computer linked to a global positioning unit (GPS) provided a record of time and position every 5 to 10 seconds during the survey. This track line was then interpolated by computer with the sightings using the time of the sightings relative to the time and position fixes generated by the GPS.

The surveys primarily used a Dehaviland Beaver on floats because of safety and greater fuel range. The plane flew at 90 knots (kt) at an altitude of approximately 65 meters (m) above sea level. Two observers recorded all birds seen, along with observation times to the nearest 5 seconds, from the edge of the floats out approximately 50 m laterally on their side. A third person ran the computer, monitored the GPS unit and output, and directed the pilot to different census routes. The sampling protocols and methodology, described in greater detail in the marine bird and mammal implementation plan (Nysewander et al., 1993), follow the general methods developed over the last two decades in California and the Pacific Northwest (Briggs et al., 1981, 1987, 1991).

The aerial surveys were stratified by effort in two levels: higher densities found near shorelines and lower densities found offshore or in open waters. Almost all of the nearshore habitat (<ca. 20 m or 10 fa) was sampled by transects that followed the shoreline in a roughly parallel pattern, whereas the offshore habitat (>ca. 20m) was sampled in a zigzag pattern.

Correction Factors for Aerial Surveys

Aircraft-based observers miss some fraction of the birds in the transect, the fraction being greatest for dark diving birds. Several alcid species fall into this category during the summer surveys, while sea and bay ducks along with loons and grebes are the species of concern during winter. This bias is not a problem in the detection of population trends as long as all surveys are carried out from the same platform. The bias does, however, make it difficult to estimate total population sizes or to evaluate what percentages of different species are being counted. Efforts began in 1993 to develop a correction factor derived from the ratio of comparable counts taken by aircraft-based observers to those taken by ship- or land-based observers. The boat surveys followed standard methodology (Gould and Forsell, 1989; Tasker et al., 1984; Conant et al., 1988).

RESULTS

The PSAMP aerial surveys recorded all bird species seen from the high tide line downward, but data analysis and summary have concentrated on the following set of species: pigeon guillemot (Cepphus columba), common murre (*Uria aalge*), rhinoceros auklet (Cerorhinca monocerata), marbled murrelet, Western grebe (*Aechmophorus occidentalis*), bufflehead (*Bucephala albeola*), two species of goldeneye (*Bucephala islandica* and *B. clangula*), three species of scoters (*Melanitta perspicillata, M. fusca,* and *M. nigra*), greater and lesser scaup (*Aythya marila* and *A. affinis*), and harlequin duck (*Histrionicus histrionicus*).

Puget Sound contains more than 3,200 kilometers (km) of marine shoreline. The PSAMP aerial surveys flew between 3,070 and 3,374 km of transects along nearshore habitat and between 1,846 and 3,220 km of transects through the offshore habitat each summer or winter aerial survey period. The survey totals include varying degrees of replicate surveys. The 1993 summer and the 1993-94 winter flights were also extended to include the American side of the western half of the Strait of Juan de Fuca. An effort was also made to increase the percentage of coverage of open water during the last two survey periods, in order to reduce variance on estimates for species encountered in concentrated feeding flocks. The percentage of each total habitat area in Washington inner marine waters sampled by the PSAMP aerial surveys ranged per each survey period from 15.1 percent to 18.3 percent for nearshore and 3.7 percent to 5.7 percent for the offshore habitat component.

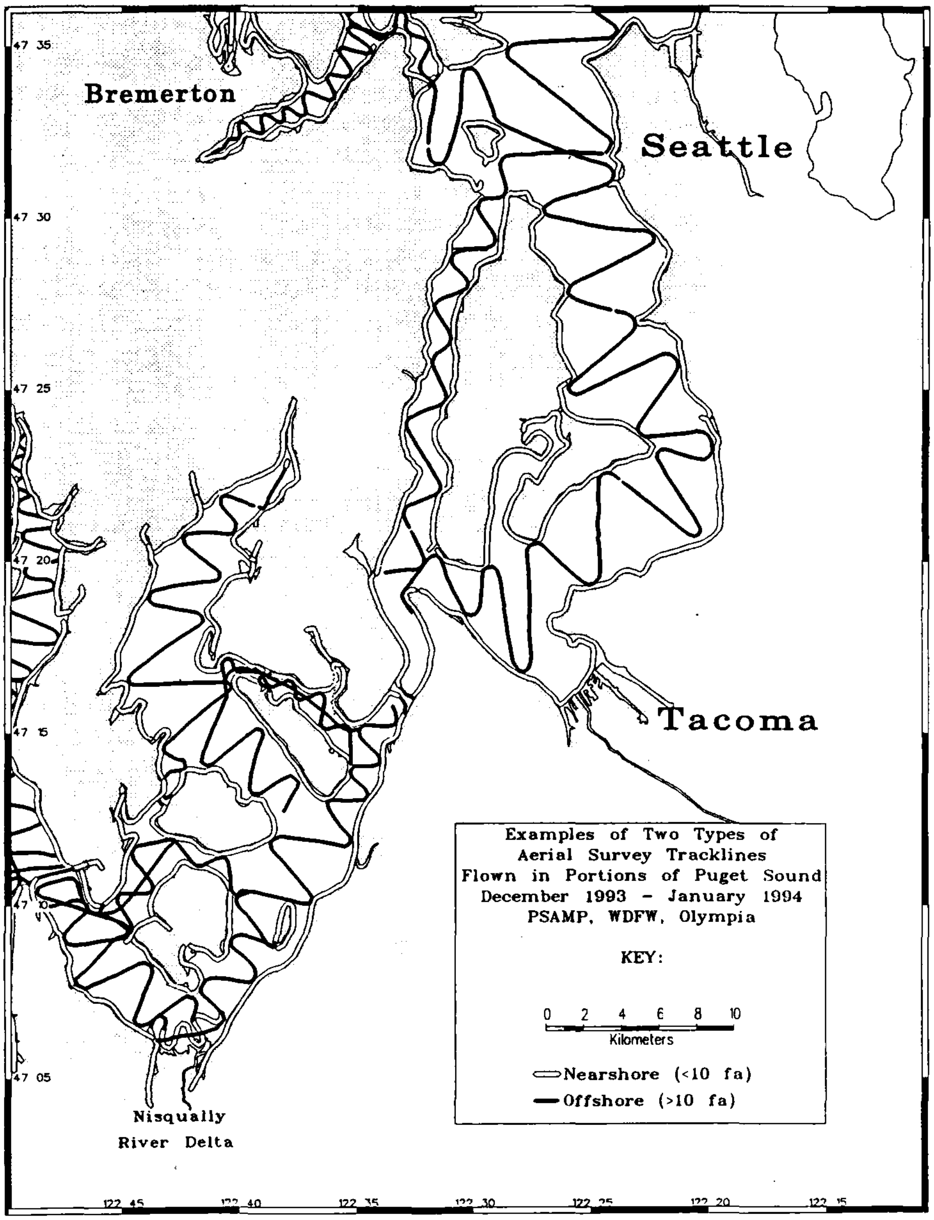

Figure 1. Two different types of aerial survey tracklines used

1992 and 1993 Summer Bird Surveys

Both summer surveys recorded the following: 1) gull and tern flocks generally distributed along shorelines, with feeding flocks of certain species, such as Heermann's gull (*Larus heermanni*), concentrating in the northern two-thirds of Washington's inner marine waters; 2) feeding flocks of alcids such as common murres and rhinoceros auklets in more open and deeper waters in the northern two-thirds of Puget Sound; 3) molting/feeding flocks of ducks along shores and river deltas; and 4) other marine birds including cormorants, pigeon guillemots, and great blue herons (*Ardea herodias*) seen along shorelines.

The total number of birds counted both on and off transects in July 1993 was 134,306, higher than the 117,633 tallied in 1992. However, in 1993 additional area was surveyed in the western portion of the Strait of Juan de Fuca. Nevertheless, the overall mapping of density for 1992 and 1993 for all bird species does

suggest some differences. The major differences appear to arise from different timing of certain species' migration through Puget Sound, especially that of gulls, from one survey period to another. El Niño conditions (ENSO) were still present on the outer coast of western United States in 1993 and may have contributed to these different migration patterns. Gulls and terns were the most numerous species group during the summer and accounted for 73 percent (98,500 individuals) of the total number of birds observed in July 1993, which is almost identical with the 72 percent seen in 1992.

1992-93 and 1993-94 Winter Bird Surveys

The winter pattern of bird distribution differed from the summer pattern both numerically and geographically. The distribution changed in the following ways: 1) larger numbers of birds used southern Puget Sound in winter than in summer; 2) waterfowl usage increased along shorelines and river deltas, with certain estuaries including the Skagit River delta and Padilla Bay containing large numbers of waterfowl and geese; and 3) grebes and loons migrated into the Sound and used protected waters (deeper waters with low currents) in southern Puget Sound, Hood Canal, the Bainbridge Island area, the Whidbey/Camano Island area, Bellingham and Padilla/Samish Bay areas, portions of the San Juan Islands, and portions of the Point Roberts/Boundary Bay area. This same general pattern of distribution was seen for both the 1992-93 and the 1993-94 winter surveys. Since the winter surveys were extended in 1993-94 to include the American side of the western Strait of Juan de Fuca, the nearshore area of the southern side of the strait was found to be an additional area containing significant numbers of certain species like harlequin ducks, marbled murrelets, and murres.

The 1992-93 winter survey recorded 620,082 birds compared to the 117,633 seen on similar transects during the 1992 summer. The 1993-94 winter surveys recorded 331,430 birds both on and off transect compared to the 134,306 tallied the 1993 summer on similar transects. Waterfowl comprised 67.6 percent (224,241) of all birds counted, which is essentially identical to the percentage (68.2 percent) seen the 1992-93 winter. The two surveys differed in several aspects: 1) Extended freezing weather during the 1992-93 survey drove many of the swans, geese, and dabbling duck species to the marine waters and shorelines, while warmer weather during the 1993-94 winter aerial surveys did not produce this effect. 2) The survey track lines for the nearshore habitat were done differently in 1993-94 for certain estuaries with wide shallow intertidal areas like the Skagit, Samish, and Padilla Bay areas, which resulted in sampling more of the available habitat but recorded lesser numbers of dabbling ducks. 3)Additional survey area in the western Strait of Juan de Fuca was covered in 1993-94, but not in 1992-93 winter survey.

Scoter distribution for Puget Sound as recorded in the 1993-94 winter survey is displayed by densities that result from the counts when combined with survey effort.

The distribution of western grebes and common murres during the same winter survey illustrates a different way of displaying data gathered and also demonstrates the differing usage patterns by different species of marine water habitats in Puget Sound. Species distribution can be mapped in greater detail with the new GPS technology.

Monitoring of Key Bird Species

Certain species were selected for emphasis in monitoring by the project's implementation plan (Nysewander et al., 1993) using criteria related to usage of or dependence upon marine waters of Puget Sound, peaks of abundance during our survey windows, and other concerns due to limited numbers or special vulnerability to mortality caused by humans. Recent reports on the status of sea and diving ducks have suggested that certain species have declined (Goudie et al., 1994 in press; Henny et al., 1994 in press) in certain portions of the Pacific Flyway. A sample data set available from two years of surveys is displayed for the diving duck species commonly seen in the winter in portions of Puget Sound.

Comparisons of counts and population estimates of these species obtained during the last two winter surveys in Puget Sound depict lesser numbers for most of these species in 1993-94 compared to the previous winter survey, but the confidence limits are large and overlap with just two years of data. Comparisons of estimates derived overall for the entire 1979 MESA study area with the estimates derived from the recent

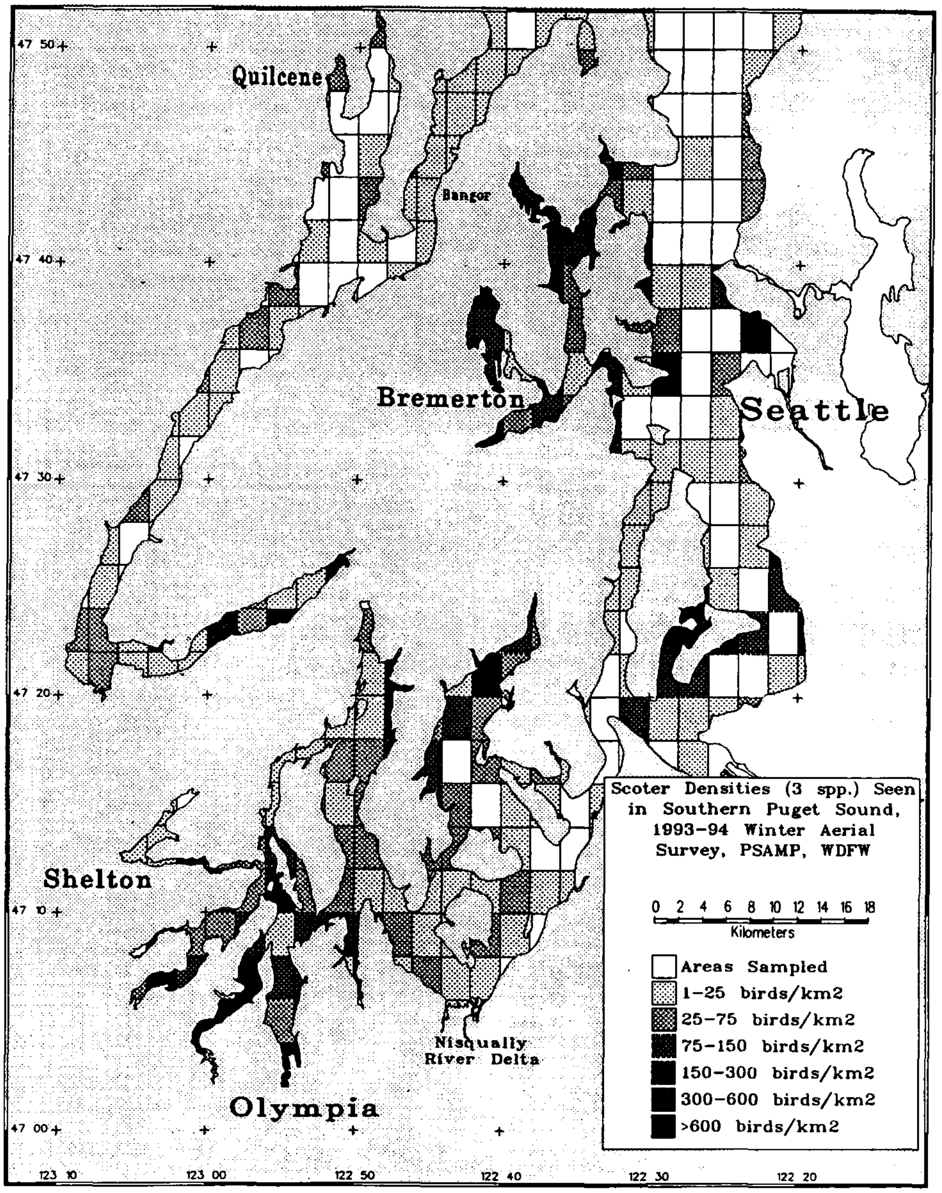

Figure 2. Scoter densities seen in southern Puget Sound, 1993-94 winter surveys

1992-94 PSAMP surveys for those same areas raises the possibility that there might be a gradual decline for goldeneyes and a larger decline for scoters.

Scoters, specifically surf scoter, are being scheduled for closer examination in the future because of these possible declines and because they have been and are target species for contaminant monitoring (Mahaffy, 1994; Henny et al., 1991).

Comparisons of Air and Boat Surveys

A pilot study began the last week of July in 1993 in the San Juan Islands. Only two days of simultaneous surveys were conducted because of weather, study design, and equipment problems. After modifications were made to transect lengths and locations, comparisons were conducted six days during September 12-23,

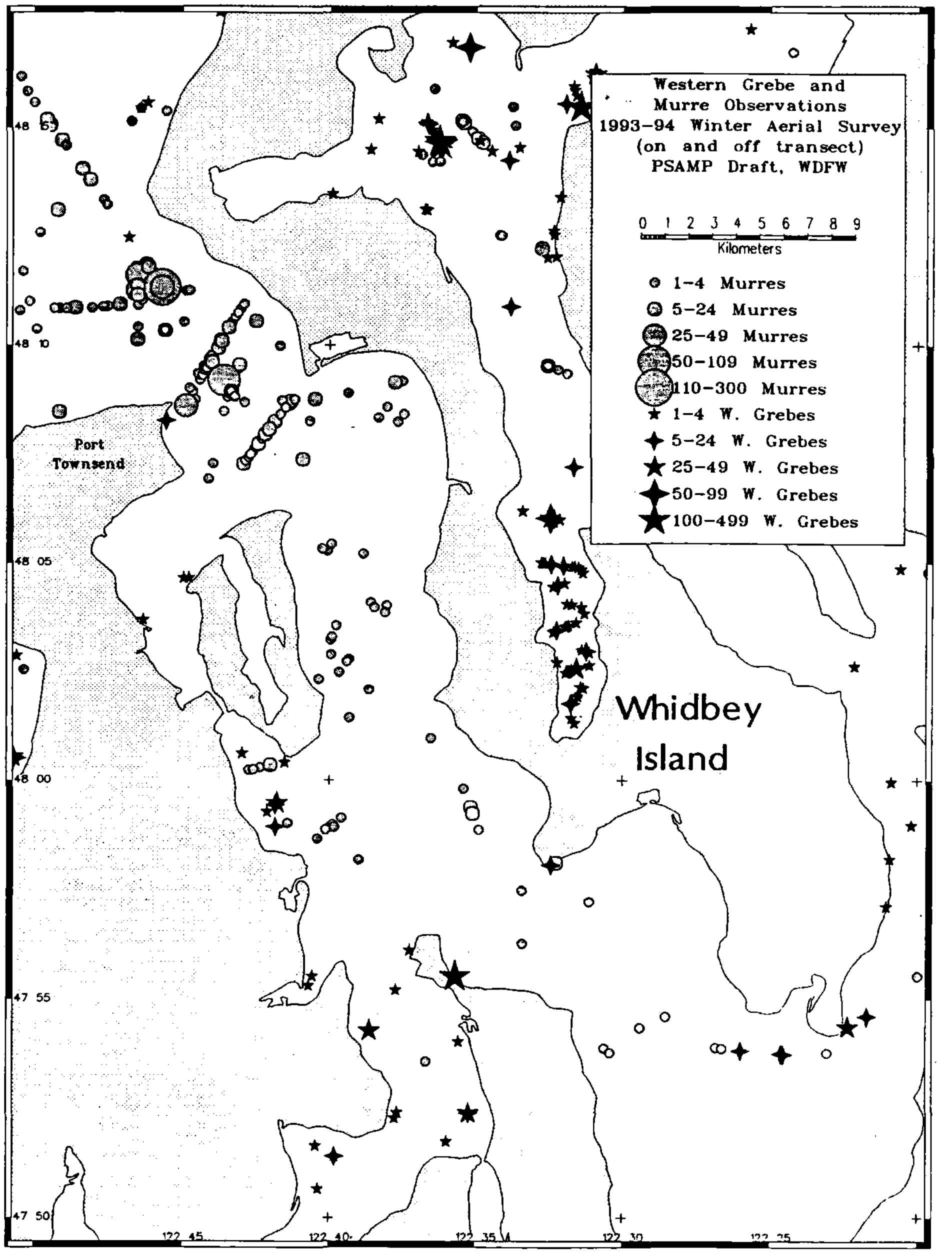

Figure 3. Different habitat usage mapped for Western grebes and common murres as seen in Admiralty Inlet area, 1993-94 winter surveys

1994. The preliminary findings suggested that large white or black species like cormorants and gulls are not underestimated by summer aerial surveys run under good viewing conditions and that diving species like alcids have boat-to-air survey ratios that usually range from 1 to 3, depending upon the species. Pigeon guillemot and marbled murrelet were the species with the highest ratios (2.52-2.99) recorded for the summer species evaluated.

Four surveys were conducted comparing air and boat surveys in the southern portion of Hood Canal between February 24 and March 8, 1994. The preliminary results for winter species of concern appear comparable to or better than the ratios seen for winter sea duck species in southeast Alaska (Conant et al., 1988). The boat counts in Alaska generally were twice that recorded by their aerial surveys. The PSAMP winter

Table 1. Comparison of counts and population estimates of diving duck species obtained December-February during 1992-93 and 1993-94 winter aerial surveys

	1992-93		1993-94	
Species	Counts On Transect	Population Estimate (±95%)[1]	Counts On Transect	Population Estimate (±95%)[1]
Bufflehead	19,085	92,775 (±17,277)	16,443	69,008 (±10,155)
Goldeneye (2 spp.)	14,402	52,783 (±9,677)	12,585	53,380 (±12,477)
Scoter (3 spp.)	32,909	155,340 (±47,069)	23,179	110,725 (±28,479)
Scaup (2 spp.)	6,399	56,695 (±40,868)	4,358	28,214 (±15,682)
Canvasback	485	1,708 (±1,315)	284	842 (±584)
Ruddy Duck	2,261	5,995 (±4,067)	2,840	8,239 (±7,408)
Oldsquaw	399	12,038 (±11,760)	327	5,233 (±5,541)

[1] Derived with PSPOP software from counts recorded only on transects.

survey recorded ratios generally between 1 and 1.5 for diving duck species. As was suspected, only a small percentage (13.7 percent) of the smaller grebe species are seen by the aerial surveys, even in the excellent viewing and water conditions used in the PSAMP survey. Results from both summer and winter comparisons will be evaluated in more detail in 1995 reports.

Creation of Synthesized Historical Database

ECI delivered the sets of synthesized historical databases on bird abundance and distribution to our program during the spring of 1993, although they did provide output from these at earlier times. This database included only the aerial, ferry, and small boat surveys conducted during the MESA studies (Wahl et al., 1981) guided by the desire to include only data that could be strictly related to a finite area in a short period of time so as to be able to create densities. When examining certain data for species like murrelets and through conversations with Wahl about MESA studies, we realized that certain areas and species were left out by this process since the first three methods did not cover all areas. Hence in 1993 we contracted with Dennis Heinemann, who created the original databases for ECI, to add point count data from the MESA studies to the synthesized historical database.

Winter Resident Shorebird Survey

WDFW, the USFWS, and Point Reyes Bird Observatory contracted with Cascadia Research Collective (Cascadia) during winter 1992-93 to identify wetlands of regional and national significance for shorebirds based on the number of shorebirds using them, and to identify important wintering areas based on shorebird abundance and species diversity. Cascadia has been organizing shorebird counts in western Washington for the Pacific Flyway Project since the winter of 1990-91, using a number of volunteers. The contract for the 1992-93 winter survey effort enabled Cascadia staff to fly some aerial surveys in conjunction with their ground surveys and to prepare a report summarizing all the results. These aerial flights allowed them to cover areas not reachable by land surveys and to evaluate how aerial and land-based surveys compared. Cascadia received a contract to conduct these surveys again during the 1993-94 winter. The surveys have been successful in documenting winter habitat use by shorebirds in western Washington (Evenson, 1993;

Table 2. Comparisons of winter[1] population estimates for diving ducks species between 1992-94 PSAMP surveys and 1979 MESA studies

Survey Type	Population Estimates (± 95%) [2]		
	Goldeneyes (2 species)	Bufflehead	Scoters (3 species)
1993-94 PSAMP Aerials (MESA area)	9,970 (±2,593)	41,739 (±7,895)	35,658 (±11,049)
1992-93 PSAMP Aerials (MESA area)	14,130 (±3,524)	65,768 (±16,462)	56,460 (±19,147)
1979 MESA All Platforms	21,393 (±8,167)	58,272 (±16,062)	162,037 (±48,878)
1979 MESA Aerials Only	17,784 (±7,640)	46,889 (±17,820)	144,311 (±38,334)

1 Winter is defined as observations gathered December through February.

2 Derived with PSPOP software from counts recorded only on transects.

Evenson and Buchanan, 1994), and the results are covered in another presentation at these proceedings.

Adult-Juvenile Ratio of Marbled Murrelets

Most major summer concentration areas of murrelets in greater Puget Sound were surveyed, except along the southern shore of the Strait of Juan de Fuca west of Dungeness Spit. The pilot study was deemed successful in August-September 1993 (Stein, 1994), and the survey was continued in August 1994 to ensure that the higher proportion of juveniles determined in this study compared to other areas is consistent. There has been interest by both USFWS and members of the Marbled Murrelet Recovery Team in using these estimates in the demographic analyses currently being prepared for this species.

Harbor Seal Census

PSAMP staff assisted Steve Jeffries from the Marine Mammals Investigations office (WDFW) and Harriet Huber from National Marine Fisheries Service (NMFS) with aerial survey and photography of harbor seal numbers at haulout sites in both August 1993 and August 1994. Huber and Jeffries covered all haulout sites for harbor seals throughout Puget Sound, which covered a larger time frame than just the August surveys. Staff time was not available for performing counts from photographs taken during the surveys; hence PSAMP funded the hiring of temporary help to complete this stage of the survey. Huber is coordinating the archiving of this survey data, which is part of a three-year NMFS project started in 1991 to determine the status and abundance of these seals in Washington and Oregon. A report summarizing the summer surveys is scheduled periodically. Contact either Steve Jeffries (206-589-7235) or Harriet Huber (206-526-6433) for further information.

Harbor Seal Contaminant Monitoring

PSAMP supported the capture, radio tagging, and biopsy of harbor seal females and pups at the Gertrude Island haulout site, primarily in the form of funding, with some staff assistance in occasional fieldwork.

This work is described in the project implementation plan and is part of a cooperative project with WDFW and NMFS. This information will be summarized at a later date. Contact either Jeffries or Huber for additional information.

Resident Gray Whale Monitoring and Identification

Cascadia Research Collective was granted a contract in 1992 to gather baseline information on gray whales in Puget Sound that would help assess their exposure to contaminants (Calambokidis and Evenson, 1993). In 1993, Cascadia continued the research conducted in 1992 and expanded their work in two areas: 1) They expanded their geographic coverage to cover all waters of Washington state. 2) They prepared a publication containing a summary of their findings and a photographic catalog of identified gray whales that reside in, rather than migrate past, Washington and British Columbia waters during the summer (Calambokidis et al., 1994). For further information, John Calambokidis can be contacted at Cascadia Research (360-943-7325).

DISCUSSION AND RECOMMENDATIONS

Briggs et al. (1985a, 1985b), Savard (1982), and Stott and Olson (1972) discuss the many variables with which aerial surveys and observers must contend. It has been recommended that aerial surveys use the same observers, plane, time of year, survey procedures, and large numbers of surveys and replicates (Gaston and Smith, 1984; Martinson and Kaczynski, 1967). The PSAMP aerial surveys attempt to follow these guidelines by only surveying when certain conditions exist (i.e., enough visibility and no wind above Beaufort 4 or 18 mph), training observers, using the same observers, and limiting length of survey periods. Comparisons of the MESA and PSAMP data encounter some problems here because several of these categories were different, but the recent ongoing PSAMP aerial surveys have consistently followed this strategy to this date and cover a larger percentage of the study area (15 percent to 18 percent for nearshore and 3 percent to 6 percent for offshore) than most aerial surveys (<5 percent) (Conant et al., 1988; Gaston and Smith, 1984).

The presence of PSAMP aerial transects in all portions of Puget Sound nearshore and offshore waters has yielded maps that characterize spatial and seasonal patterns of abundance, thus meeting some PSAMP goals. The detail in which the data can be displayed also appears useful for a number of management and environmental concerns in Puget Sound that include oil spills, gillnet mortality, contamination, disturbance, and habitat loss (Mahaffy et al., 1994). The monitoring of trends or determination of significant change is a more difficult task, however. It would be most successful if a series of continuing annual data were gathered. It would also require increasing the number of replicate surveys so as to reduce the confidence limit around each estimate.

Gaston and Smith (1984) demonstrate that survey intensity must increase with flock size to maintain the same level of accuracy. In the case of murres in Puget Sound, our analysis indicates that the standard error would be reduced by 14.5 percent if 1,441 km of transects were flown in the offshore portions of MESA regions 6 (Whatcom County), 8 (Haro Strait), and 16 (all of south Puget Sound).

Statistical analysis of changes in population size of marine birds is discussed in detail in the implementation plan pertinent to this task (Nysewander et al., 1993, pp. 42-45). Population size estimates of marine birds typically have large within-survey variances because of patchy spatial distributions, large within-year variances because of seasonality, and large among-year variances because of yearly variation in migratory patterns. The non-parametric tests for trend analysis recommended by the design contract suggest that five to 20 years of survey data would be needed for analysis depending upon the specific species selected if there were to be a reasonable chance of recognizing significant changes of any gradual nature. This is especially valid for comparisons with the historical database and its large confidence limits, caused in part by different survey platforms, observers, timing of surveys, and survey methodology. This issue should be revisited in the future if additional years of data are collected under similar survey methods and platforms.

ACKNOWLEDGMENTS

The design and formation of this project in its early stages owes much to efforts of Lora Leschner and Don Kraege. Glenn Ford, Janet Casey, and Dennis Heinemann at Ecological Consulting Inc. were key players in creating the computer programs and implementation plan needed. Chris Prescott and the Puget Sound Water Quality Authority are thanked for their review and continuing support. The skills and enthusiasm of pilots were critical for the aerial surveys to be completed under both summer and winter conditions, and the following deserve much credit and thanks: Jim Chastain, Gene Gore, and Rich Poppert with the Department of Fisheries and Bob McMahon, John Kittelson, and Tony Hope with Puget Sound Seaplanes.

The aerial survey data were collected primarily by Matt Nixon and Janet Stein with assistance from David Nysewander and Howard Ferguson. The various associated boat surveys would have been impossible but for the assistance of additional department staff from both regions 4 and 6 as well as the Oil Spill Response section in Olympia. Lora Leschner, Jack Smith, Eric Cummins, Leni Oman, and Thom Hooper are thanked for providing the following personnel: Jeff Skriletz, Barry Troutman, Jeff Bernatowicz, Ann Lettenberger, Bill Ritchie, and Joe Buchanan.

The marine mammal studies have been coordinated, led, or advised by Steve Jeffries (WDFW) and Harriet Huber (NMFS). Cascadia, specifically John Calambokidis and Joe Evenson, have been instrumental in the success of whale and shorebird contracts.

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THE PUGET SOUND AMBIENT MONITORING PROGRAM: NEARSHORE HABITATS

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GOALS AND SCOPE OF TASK

The Puget Sound Ambient Monitoring Program (PSAMP) is designed:

1. to assist agencies in their decision making characterizing and interpreting spatial data and temporal trends and identifying problem areas;
2. to take measurements to support specific program elements and measure the success of the Puget Sound Plan by providing a permanent record of significant natural and human-caused changes in key environmental indicators over time; and
3. to provide an ongoing assessment of the health of the Sound and the risk to human health from consuming Puget Sound seafood.

The 1991 Puget Sound Water Quality Authority Plan (PSWQA, 1991) designates the Washington Department of Natural Resources (WDNR) as the implementing agency for the nearshore habitat component in its Monitoring Program under Task M-2, PSAMP. The nearshore habitat program's goal is to inventory (i.e., provide baseline information) and routinely monitor the distribution and types of marine and estuarine nearshore habitats of Puget Sound using the most cost-effective methods (PSWQA, 1988). Because habitat loss is increasingly being recognized as a key environmental indicator (Levings and Thom, 1994; Thom and Hallum, 1994), and further losses should be prevented (British Columbia/Washington Marine Science Panel, 1994), results of this program are critical. The reporting requirements (products) are given in Figure 1.

1. Presentation of maps of aquatic habitat
   - Special reports—For the public and officials
2. Identification and discussion of changes in areal extent and nature of habitats
   - Special reports—For the public and officials
   - To be included in annual monitoring reports when several years' data are available
3. Calculation of total area in each habitat grouped by area, county
   - Special reports—For the public and officials
4. Graphic presentations of data and summary statistics (e.g., bar graphs)
   - To be included in special reports for the public and officials, and for specific scientific questions
   - To be included in annual monitoring reports

Figure 1. Red Book Analysis Requirements

Program implementation protocols are given in "Implementation Plan for the Characterization of Puget Sound Nearshore Habitats" (Mumford et al., 1992). Remote sensing data (multispectral digital imagery and color photography) are collected from aircraft flown over Puget Sound shorelines during the summer growing season when tide levels are at or below at -1.0′ datum. Digital images are analyzed and classified to a habitat classification scheme (Dethier, 1990) and the classified information stored in a geographic information system (GIS). Results are published in annual PSAMP reports by the Puget Sound Water Quality Authority (1993).

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Data Acquisition/Delivery

During the summer of 1991, only five flight lines were flown because of cloudy weather during the times of low tides.

During the summer of 1992, most of Puget Sound shorelines were flown by a subcontractor for the Environmental Protection Agency Environmental Monitoring Lab (EPA-EMSL). While this is the most complete data set obtained to date, it poses several challenges for analysis. The data were collected at a pixel size of 7.5 m, not 5 m as specified. No atmospheric correction was made so that only a small portion of the image can be consistently analyzed. Positional accuracy was 1-2 orders of magnitude larger than specified, making the ability to register with other data problematic.

No remote sensing data were collected during the 1993 or 1994 summer field seasons. The 1993 summer field season was halted pending the outcome of the project scoping (see below). No data were collected during the 1994 season because of inadequate time to get a viable contract after scoping and permission to proceed had been obtained.

An agreed-upon list of priority areas for image processing of the 1992 data has been drawn up from discussions with the Aquatic Resources proprietary staff and PSWQA staff. These areas are Cherry Point, Commencement Bay, Elliott Bay, Everett, Bellingham Bay, Eagle Harbor, Lummi Bay/ Lummi Island, Sinclair Inlet, Anacortes, Skookum Inlet, Padilla Bay, Quilcene, Dabob Bay, Port Susan, Budd Inlet, East Skagit Bay, Nisqually Delta, and Totten Inlet.

A personal services contract has been made with Borstad and Associates. This contract has yielded valuable information, making recommendations on specific MSS band sets for classifying nearshore habitat land-cover types of interest in Puget Sound and calibration of MSS sensor for the collection of nearshore habitat imagery data. It also provides training to DNR remote sensing staff to improve productivity and effectiveness in processing MSS digital data and classifying nearshore habitat land-cover types.

Field Analysis

Field work in 1991, 1992, 1993, and 1994 was focused on field verification ("ground truthing") of 1992 MSS imagery. The results of this field work are discussed by Bailey et al. elsewhere in these proceedings. Because of poor position accuracy of the imagery delivered, field methods have been altered to allow better use for accuracy assessment of image classification.

Database Construction and Analysis

All the field data that is associated with a GPS site location has been entered into a tabular database and checked for errors. The tabular field data has also been transferred to the GIS in order to have the information associated with the GPS locations.

The species lists from the Dethier habitat classification have also been entered into a tabular database. Bailey et al. (this proceedings) compare the species found at different habitats during our study to those listed by Dethier (1990) as diagnostic or common species for a particular habitat.

Scoping

Because of a change in funding for the Nearshore Habitat Inventory and the need to select a new vendor for data collection, the Nearshore staff spent nearly a year re-scoping the Nearshore Habitat Inventory project. The goal of the scoping was to identify the habitat information needs of the DNR Aquatic Lands Division and the PSWQA Puget Sound Ambient Monitoring Program in order to guide processing of the 1992 remote sensing data and to establish an effective and technically feasible approach for future data collection and processing.

The 1992 data is being processed to detect eight vegetation types. Data are processed first for areas of concern (see above), then for the rest of Puget Sound. This way of processing the 1992 imagery will provide the WDNR with greatly improved information on habitats protected by current policy. The original raw data will be available for additional research, such as specific analysis of habitat function, proposed project impact analysis, or change detection.

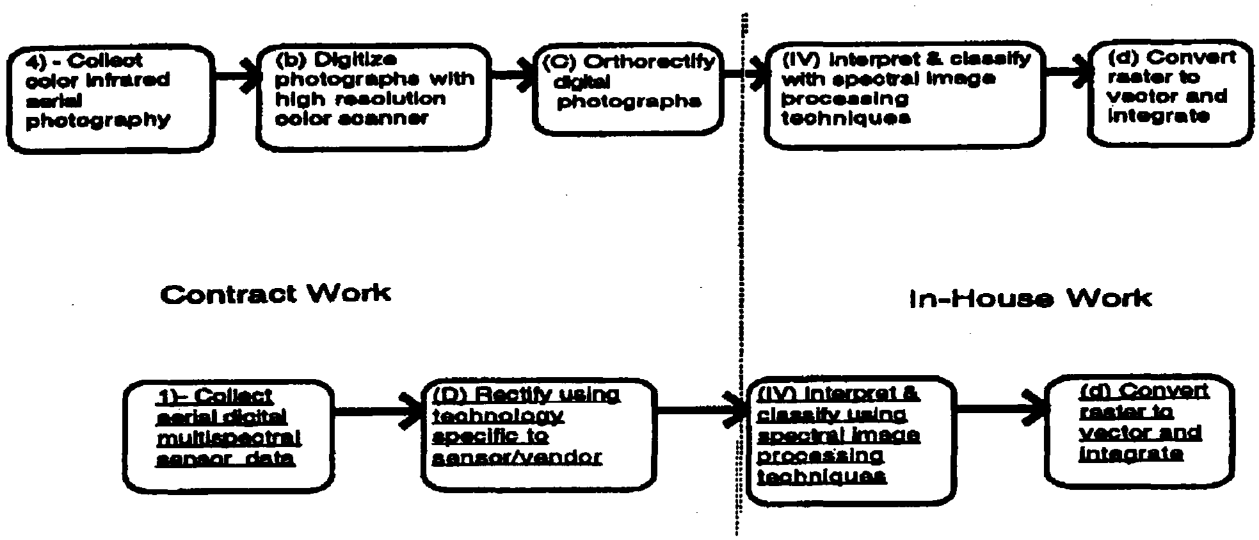

Figure 2. Nearshore habitat monitoring—Alternatives for data acquisition

Future data collection efforts will acquire digital multispectral image data with simultaneously collected color aerial photography. This approach is most capable of producing data that will meet our requirements.

Acquisition of color aerial photography is reliable, but the data available for classification and analysis are limited. MSS digital data provide the strongest set of spectral data for use in classification and change detection or cumulative impact work; however, obtaining good positional accuracies with the digital data is not as reliable as color aerial photography.

Given the priority of classification accuracy over positional accuracy, and the need to provide future analyses with the best data possible, the final recommendation relies heavily on MSS digital data, but elements of color aerial photography will be incorporated into the data collection phase so as to mitigate the risks of data-collection and positional accuracy problems.

In making a final recommendation, the following major risks were taken into account:

1. Aircraft-based mapping methods are risky because of potential bad weather, airplane mechanical problems, and technical difficulties with data collection equipment (sensor, navigation, computer, etc.).
2. Accurate rectification of aerial-based sensor data is risky, unproven, or costly in nearshore areas.
3. Examples of this type of project using aerial digital imagery are usually done on a research scale, rather than for areas as large as Puget Sound.

A detailed survey of possible vendors was undertaken to assess the "state of the art." In general, we found vendors who are able to deliver the amount of data required with experience in the particular habitat types required.

REPRESENTATIVE OR SAMPLE DATA SET—COMMENT ON SPATIAL PATTERNS

Classification/Analysis

Flight lines # 6 (Cherry Point), 48, 49, 50 (Elliott Bay), and 69 (Hood Canal) were classified using ERDAS Vers. 7.5 software to "Vegetation Thematic" classes. Tabular summaries of the areas of each class are shown in Table 1.

Examples of results are shown in the poster session "Mapping Puget Sound Nearshore Habitats."

Table 1. Areas of vegetation types in selected flight lines

"Vegetation Thematic" Class	Cherry Pt. Line #6 (area in hectares)	Elliot Bay Line #48 (area in hectares)	Elliot Bay Line #49 (area in hectares)	Elliot Bay Line #50 (area in hectares)	Hood Canal Line #69 (area in hectares)
Eelgrass	468.6	4.0	2.8	4.1	66.7
Kelp	18.3		0.8		
Green Algae	*	25.2	29.3	6.1	1.8
Brown Algae	*	0.6	1.2	2.0	0.02
Red Algae	*				
Mixed Algae	*			6.8	0.3
Salt Marsh	*			0.2	5.2
Spit/berm vegetation	*	0.7			0.1
Total vegetation	486.9	30.5	42.4	19.2	74.12

Comparison of Aquatic Resources Nearshore Inventory to Coastal Zone Atlas and National Wetlands Inventory

The Coastal Zone Atlas (CZA)(Washington Department of Ecology, 1980) and the National Wetlands Inventory (NWI) are the two most comprehensive sources for nearshore vegetation maps in the Puget Sound Basin. Both map sets were developed from aerial photo interpretation and some field verification. The Coastal Zone Atlas was published in 1977 and the National Wetlands Inventory for Washington state was published in 1987, but it was developed from aerial photography taken in the early 1980s (U.S. Fish and Wildlife Service, 1987). The Coastal Zone Atlas was developed for a purpose similar to our own inventory—to provide coastal habitat information on a regional scale that will improve management decisions in Washington state. The National Wetlands Inventory was developed to map fresh and saltwater wetlands for the entire United States; therefore, the level of classification detail for NWI is much less than that of the CZA or of our inventory. (See Table 2 for comparison between Aquatic Resources, CZA and NWI classifications.)

In the following section we have compared the "vegetation thematic" land cover classification of a few of our work areas with the maps of the same areas in the CZA and NWI. From this comparison we cannot

Table 2. Translation between nearshore vegetation classification systems for existing maps in Puget Sound Basin

Aquatic Resources Class	CZA Class	NWI Class
Eelgrass	seagrass	aquatic bed
Kelp	kelp community	aquatic bed
Green Algae	other algal community	aquatic bed
Brown Algae	other algal community	aquatic bed
Red Algae	other algal community	aquatic bed
Mixed Algae	other algal community	aquatic bed
Salt Marsh	salt meadow, salt marsh, brackish marsh	emergent
Spit/berm vegetation	vegetated spit	no corresponding class

Table 3. Comparision of data collection and interpretation methods of National Wetland Inventory, Coastal Zone Atlas and Nearshore Inventory

	National Wetland Inventory	**Coastal Zone Atlas**	**Nearshore Inventory**
Date of data collection	1980-3	mid 1970's	1992
Data source	photointerpreted color infrared photography (NHAP)	photointerpreted aerial photographs	multispectral scanner imagery and aerial photography
Scale of data	1:58,000	1973-4 1:24,000 1976-77 1:6,000	7.5m pixel 1:12,000
Scale of information	1:24,000	1:24,000	1;24,000
Minimum mapping unit	1-3 acres 0.40-1.21 ha	0.25 acre 0.10 ha	1 pixel 0.014 acre 0.0056 ha

make any substantive quantitative conclusions about "real" changes in habitat over time because the basic information (photographs), techniques used to interpret habitats, and classification systems are significantly different (see Table 3).

Differences cannot be attributed to a difference in detection ability, versus an actual change on the ground. Nonetheless, it is useful to see how our inventory will add to the existing information. Project flight lines 6, 69, 49 and the southern portion of flight line 48 are compared in more detail in Washington Department of Natural Resources (1994).

WHAT HAS BEEN LEARNED

Relevance

The classified land cover maps not only fulfill a task of the Puget Sound Water Quality Authority's Puget Sound Ambient Monitoring Program but will also be used for better management of aquatic resources by the Department of Natural Resources. WDNR, as steward for state-owned aquatic lands, is committed to managing these lands for the current and future citizens of the state sustaining long-term ecosystem and economic viability. Several other programs or issues will benefit from this information—programs such as Endangered Species Act habitat identification and protection, eelgrass management, ecosystem management by various agencies, habitat restoration activities, resource damage assessment efforts, tribal shellfish issues, and growth management act critical areas protection.

Integration With Other Tasks

There has been a decided lack of integration with other PSAMP tasks. First, few of the other monitoring tasks take place in intertidal or shallow subtidal regions. Little has been done to correlate habitat distribution and type with the occurrence of monitored organisms.

There has also been little use of the information generated to date to determine the effectiveness of other programs in the Plan (PSWQA, 1991). There have been few efforts to collect and analyze historical data on habitat changes in Puget Sound (see Thom, R. M. and L. Hallum, 1991, for a review). These tend to be general or regional in nature. This program will aid in making a more detailed change analysis possible.

The use of the habitat information has been more widespread outside the PSWQA. We have shared data with the WDFW Priority Habitat Species Program and several counties for use in their implementation of the Growth Management Act requirements.

An international effort with British Columbia has indicated that loss of habitat was the most pressing environmental issue in the shared waters of British Columbia and Washington (British Columbia/Washington Marine Science Panel, 1994; Levings, C.D. and R.M. Thom, 1994). A task force reporting to the Science

Panel has called for the inventory of habitat and development of a common protocol for inventory, classification, and database management. This program is involved in this effort.

Lanzer, elsewhere in this proceedings and in Needham and Lanzer (1993), discusses the need for data integration in the development of Puget Sound GIS. An integral part of the database is habitat information.

Proposed Changes

The protocol needs be expanded, both vertically and horizontally, to regions not now covered. These include subtidal regions (below the depth at which features are discernible—about 1 m below surface), the Strait of Juan de Fuca, and the outer coast and estuaries. Loss of important habitats at the lower limit of light penetration is not being properly monitored.

As discussed above, the protocol needs to be coordinated with similar habitat inventories and classifications in British Columbia.

For full realization of the program's goals, any future data acquisition must be collected with spatial use clearly designed into the initial planning.

ACKNOWLEDGMENTS

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PUGET SOUND RESEARCH '95

SESSION 1B

COASTAL EROSION MANAGEMENT STRATEGY

Session Chair:

Douglas Canning
Washington Department of Ecology

THE RATE AND CHARACTER OF SHORELINE EROSION ON PUGET SOUND

Hugh Shipman[1]

INTRODUCTION

Puget Sound consists of approximately 3,000 km of shoreline—most of it either eroding or subject to erosion. As populations in the region grow, pressure to develop the shoreline will increase. A majority of the new development will be single-family residences, built along rural, forested shorelines. The ecological cost of this development for Puget Sound may be high. In addition, property owners will feel compelled to protect their valuable investments and may choose to install bulkheads or seawalls for erosion protection.

Wise management of the shoreline, whether intended to protect natural ecosystems or to prevent the loss of economically valuable property, requires a thorough understanding of shoreline processes and specifically of shoreline erosion. This paper summarizes much of what we know about the nature of erosion on Puget Sound, along with limited information on the rates at which it occurs.

GEOLOGIC SETTING

Puget Sound and its associated waters lie within the Puget Lowland, a tectonic trough located between the Cascade and Olympic mountains. The Puget Lowland has been repeatedly occupied by glaciers, the most recent of which retreated from the area about 12,000 years ago. The glaciations created the north-south fabric of the topography and deposited much of the sediment that currently blankets the region. Surficial geology consists primarily of glacial outwash, till, and glacial-marine drift, along with interglacial fluvial deposits and lakebeds.

Puget Sound has mixed-semidiurnal tides, with maximum high tides occurring near the winter solstice. The tidal range increases southward into Puget Sound from less than 3 meters in the north to more than 5 meters in the Olympia area. The Puget Lowland is currently subsiding as a result of tectonic movements. Sea level is rising more rapidly in the southern sound (3.4 mm/yr at Tacoma) than in the northern sound (0.6 mm/yr at Friday Harbor) (Shipman, 1990).

Puget Sound is largely protected from open-ocean wave conditions. Waves within Puget Sound are generated locally during storms, and fetch is the significant limiting factor for wave formation. Even where fetch is relatively great, the narrow bodies of water reduce the effective fetch significantly. Maximum wind speeds are generated during winter storms, which usually result in southerly winds over Puget Sound and northerlies over Georgia Strait (Downing, 1983).

Winds generally parallel the elongate water bodies, leading to highly oblique wave approach on most shorelines. Deep water is located relatively close to shore along most shorelines; therefore waves are relatively unaffected by the bottom until they reach the beach. This results in minimal refraction of waves and little tendency for waves to break offshore.

The present Puget Sound shoreline, consisting of a shore platform, coastal bluffs, and numerous barrier beaches, has largely formed since global sea level rise slowed near its current position about 5,000 years ago. The highly convoluted shoreline is divided into a large number of discrete littoral cells that range from a few tens of meters to a few tens of kilometers in length (Schwartz et al., 1989). Littoral transport volumes are correlated with fetch but are generally small, reflecting the moderate wave energy regime, the small littoral cells, and the coarse beach material (Wallace, 1988).

Beach sediment is derived largely from coastal bluff erosion. Several major rivers empty into Puget Sound, but beach-size sediment is deposited in the lower river channel or in the delta. Small streams and drainages that reach the shore may provide sediment in some areas, but we believe this is a minor

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component on most shorelines at this time. Beach sediment often reflects the particle size composition of local bluffs.

SHORELINE EROSION

Puget Sound's shoreline consists of several general shore types. The most prevalent is that of a coastal bank or bluff with a narrow fronting beach. The distinction between low banks and higher bluffs is often made but is somewhat arbitrary and unnecessary here. Coastal bluffs are found in virtually all parts of Puget Sound. The second common shoreline type is a rocky coast, often with minimal beach development. Such shorelines are particularly common in the San Juan Islands. A third common shore morphology is a depositional landform such as a sandspit or barrier beach. Such beaches are found throughout the Sound. A fourth shoreline type is the deltaic shoreline, found where major rivers enter the Sound, although few of these remain in their natural state. A final shoreline type includes those associated with protected lagoons and marshes. In this paper, we limit our discussion to shoreline bluffs, depositional beaches, and rocky coasts, since they are the locus of most of the new development activity.

Erosion of Shoreline Bluffs

Coastal bluffs comprise the largest single class of shoreline on Puget Sound. We include in this category all shorelines formed on non-bedrock uplands, ranging from banks less than several meters in height to high bluffs rising over 100 meters. Coastal bluffs are generally carved into a sequence of glacial and interglacial sediments, including fluvial sands and gravels, coarse outwash deposits and lakebed clays, as well as till and other drift from several glacial periods. Morphology varies greatly, from vertical, unvegetated bluffs to gradual slopes with mature forest cover. Bluffs are typically fronted by a sand or gravel beach that forms a thin wedge on a relatively flat erosional platform.

The erosion of coastal bluffs and cliffs has been described on many shorelines (for example: McGreal, 1979; Kamphius, 1987). In general, bluff erosion is a cyclical process in which wave-induced erosion alternates with gravity-induced mass-wasting. Waves remove debris and undercut the base of the slope, leading to the development of an unstable slope profile, allowing mass movements to occur. One significant implication of this is that bluff recession rates are highly episodic, with rapid erosion events punctuating long periods of relatively little change.

Coastal slopes are susceptible to a wide variety of mass-wasting mechanisms, depending on geology, stratigraphy, hydrology, vegetation, and other factors (Tubbs, 1974; Thorsen, 1987; Macdonald et al., 1994). These mechanisms include raveling of unconsolidated sands and gravels, block falls, shallow slides and flows, and large rotational slumps. Soil creep may be a significant factor on many coastal slopes. The Coastal Atlas (Washington Department of Ecology, 1978) contains detailed maps of coastal slope stability, including the locations of large historic and prehistoric slides. Shallow slides and flows are probably the most common form of slope failure on Puget Sound coastal bluffs. They typically involve only a weathered layer 1 meter to 2 meters deep but may range in size from several cubic meters to tens of thousands of cubic meters. These slides may be triggered by wave action; however, they often result from geologic weakness developed along perched water tables and may occur well above the base of the slope.

Long-term bluff recession rates generally depend on three factors: the wave energy reaching the site, the geology of the bluff, and the character of the fronting beach. The wave environment affects the energy available to erode and transport material. Geology controls the resistance of the bluff toe to erosion as well as the degree to which mass-wasting processes can deliver easily erodible debris to the base of the slope. The fronting beach determines the frequency with which waves directly attack the base of the bluff and the degree to which wave energy can be dissipated without eroding either the bluff toe or the erosional platform.

The toe of a typical bluff may be located about 0.5 m above MHHW. For waves to erode the toe, storm waves must coincide with high spring tides. Wave-induced toe erosion is generally concentrated during a very few events during the period of November to January, based on the seasonal occurrence of significant windstorms and the year's highest tides.

Removal of material from the toe of the bluff would be a self-limiting process were it not for the continued lowering of the beach and wave platform. Kamphius (1987) has pointed out that this downcutting is the limiting factor in the recession of bluffs composed of coherent sediment. The rate of downcutting depends on the lithology of the erosional surface and on the volume and character of the beach material.

The beach is a crucial factor in protecting the bluff from wave action. Jacobsen and Schwartz (1981) noted that beach width generally increased downdrift within a littoral cell. The additional width decreases the frequency with which waves can act directly on the bluff. In addition, the additional beach volume provides a buffer against large storms.

Bluff recession rates can be determined by several direct techniques, such as the analysis of old aerial photographs, survey records, and historical documents. Indirect methods, such as inferences from the age of undermined bluff vegetation or from the width of erosional shore platforms, may be useful but often are not sufficient for quantitative analysis and may only provide a minimum or maximum bracketing rate. Virtually all methods are limited by the generally slow rate of recession, its episodic character, and the poorly documented record. The amount of recession expected over a several decades may simply be too small to map accurately, particularly given the scale of errors associated with many of the techniques. The highly episodic nature of bluff recession means that a very long period must be considered in order to determine an accurate average erosion rate.

Qualitative evaluations of bluff erosion may be based on the steepness of the bluff or the amount of bluff vegetation. Bare, vertical bluffs are interpreted as eroding rapidly, whereas heavily vegetated, gradually sloping bluffs are interpreted as relatively stable. This technique is valuable, particularly at a reconnaissance level, and provides a good measure of the relative role of wave erosion and upslope mass-wasting. Caution must be taken, however, since vegetation and morphology may both depend on numerous additional factors, including lithology.

The Washington Coastal Atlases (Washington Department of Ecology, 1978) map the erosional character of the shoreline based largely, we believe, on interpretations of a single set of oblique aerial photographs. Keuler (1988) also mapped the shoreline according to its erosional character in the Port Townsend 1:100,000 quadrangle, which covers large parts of Skagit, Island, and Jefferson counties. In both cases, the classification is qualitative.

The literature contains relatively few studies that contain quantitative erosion rates (see Table 1), and virtually all are in the north and central parts of the Puget Lowland. Keuler (1979) determined erosion rates for unconsolidated Pleistocene deposits in Skagit County, finding values ranging between approximately 1 and 12 cm/yr. The difficulty of separating out the influence of beach characteristics and wave exposure prevented conclusions about consistent differences between different types of materials. We note, however, that bluff offsets are sometimes found along shorelines where distinct lithologic changes occur, and that particularly resistant glacial tills or cemented gravels may form distinct promontories, indicating that lithologic factors are important, even within the Pleistocene deposits.

In addition to the qualitative mapping mentioned above, Keuler (1988) determined specific erosion rates at numerous sites. Only those with at least 20 years of record (and therefore those with greater accuracy) are included in Table 1. One important conclusion was that erosion rates for these bluffs were closely related to fetch, and therefore to wave energy, if one considered the volume of material eroded, rather than simply a linear distance.

In general, the highest erosion rates recorded on Puget Sound and in the Georgia Strait occur where fetch is great. Van Osch (1990) cites bluff recession rates of up to 30-50 cm/yr at Point Grey near Vancouver, B.C., and of 60 cm/yr at Cowichan Head near Sidney, B.C. These sites consist of glacial sediments and are exposed to substantial fetches. Studies of historic shoreline changes at Ediz Hook in Port Angeles indicate that bluffs west of the city receded several feet per year before the armoring of the shoreline (Galster and Schwartz, 1989). This site is located on the Strait of Juan de Fuca and is considerably more exposed than other sites discussed in this paper.

Table 1. Erosion rates of coastal bluffs on Puget Sound

Location[1]	Rate (cm/yr)	Fetch (km)	Source
Baby Island, Whidbey Island	13	15	Keuler, 1988[2]
Maylor Point, Whidbey Island	15	15	Keuler, 1988
Penn Cove, Whidbey Island	6.5	5	Keuler, 1988
Mutiny Bay, Whidbey Island	11	10	Keuler, 1988
S. of Lake Hancock, Whidbey	4	20	Keuler, 1988
Rocky Point, Whidbey Island	14	>50	Keuler, 1988
Camano Island, west side	3	10	Keuler, 1988
Smith Island	69	>50	Keuler, 1988
North Beach, Quimper Peninsula	6	>50	Keuler, 1988
Shannon Point, Fidalgo Island	20	10	Schwartz, 1971
Skagit County (mean of 6 sites)[3]	7.6 (± 2.7)	---	Keuler, 1979
Skagit County (mean of 26 sites)[3]	4.9 (± 3.4)	---	Keuler, 1979
Port Williams	30	50	Ecker et al., 1979
Sequim Bay	6	< 5	Ecker et al., 1979
Port Angeles	90-150	>50	Galster and Schwartz, 1987
Point Grey, B.C.	30-50	>50	Van Osch, 1990
Cowichan Head, B.C.	60	>50	Van Osch, 1990

[1] Note that sites were selected based on available data, not on their representativeness of regional erosion rates. We suspect this sample is biased toward sites with rapid erosion.
[2] Sites from Keuler (1988) limited to those based on greater than 20 years of record.
[3] The larger set of sites (26) includes indirect measurements that may provide a low estimate of rates. The small subset of sites (6) may better reflect an average rate.

Schwartz (1971) determined an erosion rate of about 15 m in 76 years in glacial drift at Shannon Point on Fidalgo Island, west of Anacortes. Ecker et al. (1979) estimated bluff recession rates in the Sequim vicinity, suggesting a rate of 30 cm/yr on exposed bluffs at Port William and 6 cm/yr for bluffs on the west side of Sequim Bay.

The width of the erosional shore platform provides a useful constraint on late Holocene shoreline recession rates. Care must be taken in interpreting this feature, but if analysis is limited to a clearly erosional surface (based on the presence of sea stacks or coarse lag deposits), then a minimum erosion rate can be established (Keuler, 1979). The shore platform along Puget Sound ranges in width from a few tens of meters to more than 300 meters, which, based on 5000 years of recession, implies erosion rates from less than 1 cm/yr to more than 60 cm/yr—not inconsistent with the range of rates obtained through more direct methods.

In conclusion, we find bluff recession rates vary greatly in Puget Sound, and may do so over very short distances. The highest rates of erosion occur in those areas subject to the highest wave energy, which is largely controlled by fetch. Lithology may be important but is difficult to separate from the influence of the other factors. Even when lithology is conducive to rapid erosion and fetch is large, recession rates may remain very low if there is a substantial fronting beach or wide backshore, as might be found near the distal portions of a littoral cell.

Erosion of Bedrock Shorelines

Bedrock shorelines are found in the San Juan Islands, on Fidalgo Island and the northern portions of Whidbey Island, in portions of Whatcom County, on the western side of Hood Canal, and in the central Puget Sound area between Seattle and Bremerton.

Keuler (1979) found that rates of erosion on bedrock varied by more than an order of magnitude, but that rates were still considerably slower than on shores composed of unconsolidated Pleistocene sediments. He identified a consistent difference in rates between massive rocks and those with dense jointing or that were otherwise more erodible. Actual erosion rates on bedrock averaged about 0.6 cm/yr, but ranged from nearly 0 to about 1 cm/yr.

Restoration Point, on the southeastern tip of Bainbridge Island, west of Seattle, provides additional information on bedrock erosion rates. This area is believed to have been uplifted approximately 7 meters during a large earthquake on the Seattle Fault, about 1160 years ago (Bucknam et al., 1992). The pre-uplift wavecut terrace is clearly exposed above the range of tides, and a new wavecut terrace has formed within the modern intertidal zone. It is cut into relatively weak sedimentary bedrock of the Tertiary Blakely formation. This terrace is variable in width, but in places along the south side of Restoration Point it reaches at least 100 meters in width. This implies an erosion rate of about 6 cm/yr, on a site with no protective beach and a fetch of about 20 km to the south.

Erosion of Depositional Beaches

Puget Sound contains many depositional beaches—sand spits, barrier beaches, or what are colloquially referred to as "accretion beaches" (Bauer, 1973). The large number of relatively small such features is related to the convoluted shoreline and the large number of discrete littoral cells (Shipman, 1993). Although these shorelines are formed by the net deposition of sediment or the accretion of material, both short-term and chronic erosion are common.

On unmodified beaches, erosion is a typical seasonal response to winter storm waves or a one-time response to a major storm. Overwash may occur under extreme events, sometimes accompanied by minor breaching. Such erosion is often short-lived, with the beach regaining its original profile the following summer or within a few years. A more persistent form of beach erosion occurs on barriers that are actively migrating. This landward migration of the active berm typically occurs as adjacent bluffs recede, such as occurs in the case of the barriers at Swantown and Lake Hancock on the west side of Whidbey. Among the evidence for this migration are exposed peat ledges on the seaward-facing foreshore, remnants of an over-ridden back-barrier marsh (examples include the north side of Squatter's Point near Hansville and Meadow Point in Seattle).

Erosion of barrier beaches may also be a response to human-induced reductions in longshore sediment supply, such as has occurred at Ediz Hook near Port Angeles (Galster and Schwartz, 1987). Armoring of coastal bluffs west of the city, combined with the damming of the Elwha River, led to a significant reduction in littoral sediment volumes, and serious erosion of the spit resulted. A similar process has occurred at Meadow Point in Golden Gardens Park in Seattle. The construction of the Great Northern railroad grade near the turn of the century led to a significant reduction in sediment supply from adjacent bluffs and Meadow Point, a small cuspate foreland, has retreated more than 60 feet since 1936.

SUMMARY

Rates and styles of shoreline erosion vary greatly within Puget Sound, based not only on obvious morphological distinctions (barrier beach vs. coastal bluff), but also on rapid longshore variations in wave exposure, lithology, and beach condition. Erosion is also highly episodic since it is related to periodic mass-wasting events and infrequent storm/tide combinations. This variation makes any simple characterization of erosion or erosion rates highly unrealistic.

The importance of the beach in limiting erosion rates has significant ramifications for a littoral system largely dependent on coastal bluff erosion for its sediment supply. Any reduction in longshore drift, including that resulting from updrift erosion control, may lead to increased erosion rates and the further demand for more erosion control. The degree to which this occurs will depend on individual sites, but it supports concerns about the cumulative impacts of shoreline armoring.

Shoreline erosion is not a serious problem except in a cultural context. The erosion of an undeveloped shoreline is not a natural hazard. Unlike accelerated surface erosion (and resulting sedimentation) caused

by poor agricultural or land development practices, coastal erosion is not an environmental threat. Shoreline erosion can be a serious problem on a developed shoreline, but the relatively slow erosion rates typical of Puget Sound suggest that relatively minor setbacks could reduce much of the need for seawalls and bulkheads. Regardless, our knowledge of shoreline erosion indicates that wise shoreline management must consider the shore as a complex system, where actions in one location may have consequences at another.

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PUGET SOUND WIND WAVE ANALYSIS

Vladimir Shepsis[1], George M. Kaminsky[2], David Simpson[3], and David Orders[4]

INTRODUCTION

Knowledge of the regional wave climate is essential to controlling pollution effects, protecting living resources, and understanding physical processes in Puget Sound. Wind-generated waves significantly influence nearshore habitat. Wave motion increases water turbulence, generates currents, suspends and transports sediments, and can cause accretion or erosion of the nearshore bottom. These physical processes determine the distribution and abundance of many living resources. For example, the substratum composition and stability typically determine the biological function and productivity of the nearshore. Accurate wave predictions are also important for engineering activities, especially shore protection, beach enhancement, the structural design of marina and port facilities, navigation improvements, and operation of waterborne transportation.

To date, no comprehensive effort has been made to develop consistent wave information for the regions of Puget Sound. Traditionally, wave characteristics required for coastal projects in Puget Sound have been obtained for specific project areas by applying computation procedures of the Shore Protection Manual (SPM) and/or various computer models. The Automated Coastal Engineering System (ACES) developed by the U.S. Army Corps of Engineers is a commonly used software to predict wind wave parameters in deep and shallow waters, given the wind speed, fetch and depth conditions.

However, because of complex configuration, morphology, and local wind sheltering effect, it is difficult to apply predictive models to Puget Sound. Doing so requires judgment and verification. Significant differences between measured and predicted waves have been recognized in studies, which are discussed below.

This paper presents preliminary analyses of the applicability of SPM and ACES to predict wind wave conditions in central Puget Sound near Elliott Bay. The analyses are of data from historical studies and the Washington Coastal Data Information Program (WCDIP). The results are expected to be updated and modified as additional wave data collected by WCDIP are analyzed. A more complete database of wind and wave measurements is needed to complete a comprehensive Puget Sound wave hindcast and analysis study.

OBJECTIVES

This paper proposes:

- to analyze applicability of various computation procedures to predict wind waves in central Puget Sound; and
- to propose development of actual wave database for Puget Sound.

PUGET SOUND WAVERIDER BUOY

In September 1993, the Washington Coastal Data Information Program, managed by the Department of Ecology and the U.S. Army Corps of Engineers, started a wave monitoring program in the Puget Sound. A

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Waverider buoy was stationed in central Puget Sound just north of Elliott Bay, in the midchannel area, about 2 miles southwest of West Point, as shown in Figure 1. Water depth at the buoy location is approximately 720 ft.

The Waverider is a surface-following buoy that measures vertical movement by an accelerometer located in the lower hemisphere of the buoy. The accelerometer is mounted in such a way as to negate lateral movement and tilting. A double integration of the measured acceleration is performed, and the resulting value, representing relative vertical position, is used to modulate the frequency of an AM radio carrier wave. This signal is then transmitted by the buoy. The resolution of wave height is +/- 2 cm, and the minimum wave period that the buoy can follow is one second.

There are different options to obtain Waverider data:

- Via NOAA Weather Radio frequency. Limited wave data (range of significant wave measured) is reported on three-hour basis.
- Via Department of Ecology and Scripps Institution of Oceanography. Historical and near real-time (three-hour) significant wave height, period, and energy spectrum can be provided upon request. Unfortunately, the Scripps reports cut off the energy content of the spectrum at 0.2 Hz (period of 5 seconds).
- Directly from the Waverider (real-time) by any receiver capable of tuning in the 27000-29999 KHz band.

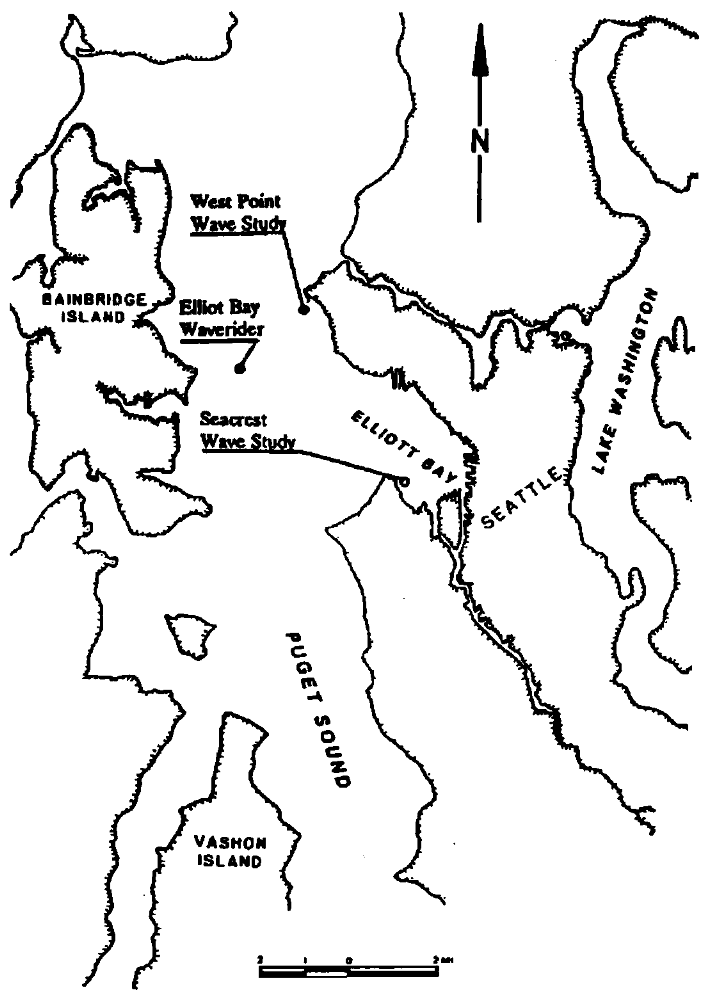

Figure 1.

The latter source has become available since development of the Datawell Waverider acquisition software "Wave Watcher" by Orders Associates. Wave Watcher software converts the buoy's radio signal into a real-time wave trace and calculates significant wave height, wave period, and wave spectrum. Wave Watcher uses the audio output from the headphone or auxiliary speaker jack of the pertinent receiver.

The Puget Sound Waverider buoy and Wave Watcher software have created the unique opportunity to obtain actual wave parameters, and test wave generation and prediction models for Puget Sound conditions. It also permits use of the wave data in real time.

HISTORICAL STUDIES

We have identified three studies that observed differences between actual and predicted wave parameters by the SPM technique: Christensen and Hevner (1981), Downing (1983), and Nelson (1986). Results of these studies are discussed below.

Case 1

Downing (1983) analyzed the general wind wave pattern in Puget Sound. He indicated that the complexity of Puget Sound morphology and bathymetry contributes uncertainty to wave characteristics predicted by classical methods. The range of these differences for significant wave height was estimated to be 7 percent to 77 percent; wave period was estimated to differ by -24 percent to 10 percent.

Case 2

Christensen and Hevner (1981) investigated the Seacrest site in Elliott Bay. They recorded wave and wind data during the period October 1980 to May 1981. The wave instrumentation was fixed to a group of pilings 200 feet offshore in 60 feet of water. The equipment included an anemometer for wind speed, a vane for wind direction, and two recording wave staffs.

Data from the anemometers and wave staffs were processed to obtain wave energy spectral characteristics: significant wave heights, magnitude of the spectral peaks, and frequencies associated with these peaks. Wave characteristics were computed with the SPM procedure for various wind directions. The fetch varied from well protected to clear and unobstructed. The prevailing winds for this site observed during the measurement period were NNW, SSE, and NW with the fetch estimated lengths of 1.8, 2.3, and 9.9 nautical miles, respectively.

Significant wave heights obtained from measured and computed waves generated by NNW wind conditions are presented in Table 1.

The table shows there are significant differences (inconsistencies) between measured and computed values. The difference increases with increasing wave height (wind speed). For example, for wind speed of 50 knots, the difference between predicted and measured wave heights exceeds 125 percent of measured value. The situation (inconsistency between measured and computed wave heights) would not change if other wave fetch were considered.

Table 1. Seacrest (Elliott Bay) study measured and computed wave heights, NNW wind

Wave Height (m)	Wind Speed, knots				
	10	20	30	40	50
Computed	0.78	1.45	2.09	2.7	3.31
Measured	0.56	0.85	1.08	1.29	1.47
Difference (%)	39.1	70.6	93.5	109.3	125.1

Table 2. West Point (Elliott Bay) study measured and computed wave data

Wind Speed (knots)	Significant Wave Height (ft)		Wave Period (second)		Percent of Error	
	Meas.	Pred.	Meas.	Pred.	Height	Period
13	1.5	1.3	2.8	2.5	13%	11%
13	1.8	1.3	3.0	2.5	28%	17%
14	2.1	1.4	3.3	2.6	33%	22%
NA	4.0	NA	4.3	NA	NA	NA

Case 3

The data from Nelson and Broderick (1986) documented differences between measured and computed wave parameters. These data were collected during the Floating Breakwater Prototype Test Program in northern Elliott Bay near West Point. Wind and wave data were measured for approximately 18 months during the period 1981-1983. Five wave gages were deployed at the testing site at depths between 30 and 50 ft. An anemometer was installed at approximately 30 ft above MLLW and recorded wind speed and direction continuously.

More than 20 different storm events were recorded during this period. The maximum wave height recorded was more than 4 ft; the corresponding wind speed was 60 knots. Most often, storm winds were in the 20- to 40-knot range with wave heights between 2 and 3.5 ft.

Wave heights for the site were estimated with SPM methodology for the same storm events. The comparative results of estimated and measured wave data for some storms are presented in Table 2. As with the Christensen and Hevner 1981 results, the differences between measured and predicted wave parameters are in proportion to wave height. However, the percentage differences are less than those identified in Case 1 and Case 2 studies.

DATA ANALYSIS FROM THE PUGET SOUND WAVERIDER BUOY

Nearly continuous Puget Sound Waverider data from September 1993 to December 1994 were compiled and analyzed. Computed wave parameters included significant wave height, period, and energy spectrum. The digital data obtained from the Waverider were processed to eliminate noise and non-wind waves from the record. The procedure included two steps:

- recorded wave data that occurred during wind speeds less than 10 mph were removed from further consideration; and
- the remaining heights less than 1 ft were filtered, based on the assumption that they represented noise or non-wind waves.

Screening and analyzing the data revealed 19 recorded wind wave events with height more than 1 ft. Total duration of all these storms was 114 hours. Maximum significant wave height recorded was 3.3 ft with a peak period of 5.1 sec occurring with 30 mph SSW wind.

Wind waves with significant heights from 1.0 ft to 1.3 ft were observed over 40 percent of all time. Wave heights ranging from 1.3 ft to 2 ft occurred more than 25 percent of the time, 15 percent of the time wave height ranged from 2 ft to 3.2 ft, and approximately 10 percent of the time wave height exceeded 3.2 ft (see Figure 2).

Return periods of extremal significant wave heights were calculated and are presented in Figure 3. Wave height data for extremal analysis was limited, and this effort represents the first attempt to estimate storm conditions for central Puget Sound. It should be considered preliminary and must be verified with a longer wave record that includes additional storms.

Wave characteristics predicted with ACES were compared with Waverider data for individual storm events. Four storms were selected for this analysis, and are described in Table 3.

Table 3. Representative storms in Elliott Bay selected for detail analysis

Date	Wind Direction	Wind Speed (Gust) (mph)	Duration (hour)
11/21/93	South	31(39)	3
11/22/93	North	29(35)	6
2/7/94	North	33(34)	3
11/30/94	South	31(35)	6

The predicted and recorded wave parameters, significant wave height and period are provided in Table 4. Winds for the storm periods were measured at nearby West Point and data were obtained from NOAA National Weather Service.

Analysis indicates that differences between measured and calculated wave parameters exceed 60 percent. The significance of the differences is discussed below.

Measured and computed (hindcast) wave parameters were compared to test the applicability of the ACES wave prediction procedure. The surface variable density spectrum of the wave time series measured from the Waverider was calculated with Fast Fourier Transform for various phases of the November 22, 1994, storm event. The JONSWAP (Hasselmann et al., 1973) spectrum was callculated with the (empirical) spectra developed from measured water surface displacement and from the JONSWAP formulation, which are compared in Figure 4.

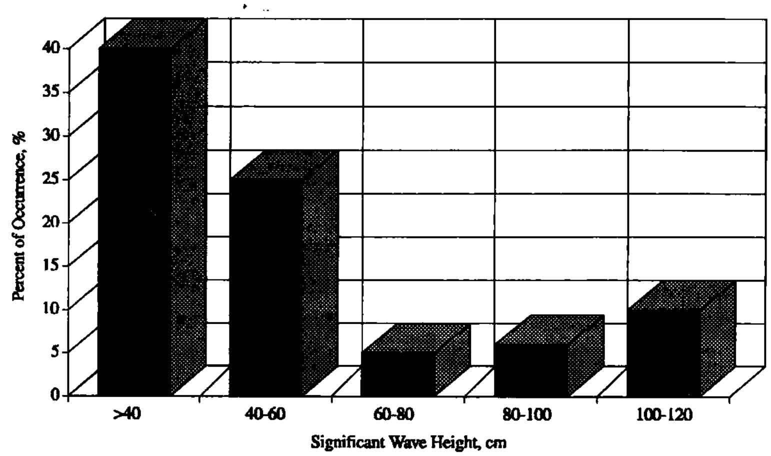

Figure 2. Waverider buoy data statistics period September 1993-November 1994

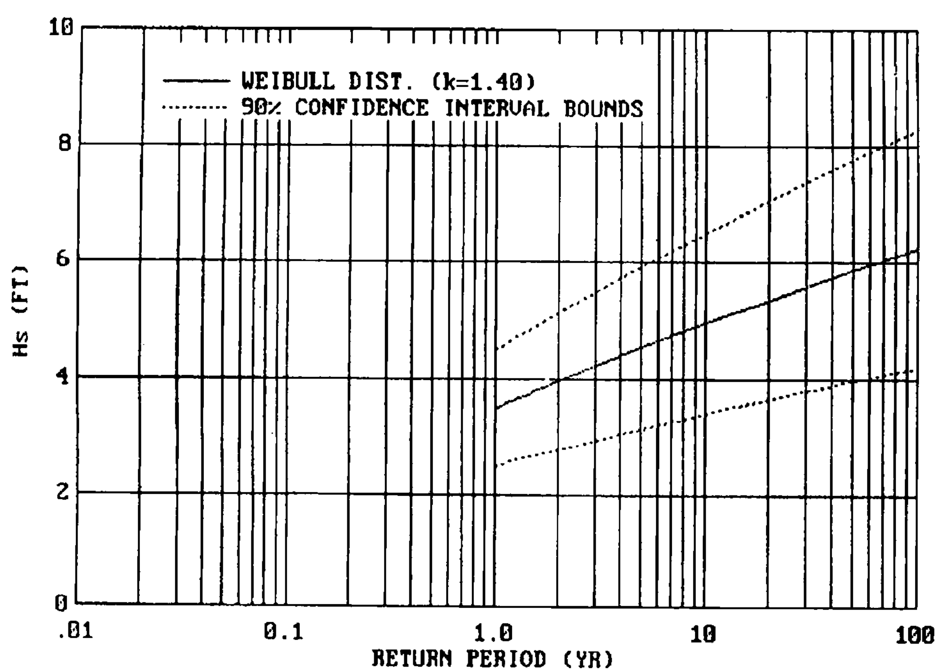

Figure 3. Extremal significant wave height distributions

Table 4. Elliott Bay Waverider significant wave height data vs ACES computed data

Date	Significant Wave Height (ft)		Wave Period (sec)		Percent of Error (%)	
	Meas.	Pred.	Meas.	Pred.	Height	Period
11/21/93	1.1	2.9	5.0	3.5	160	42
11/22/93	3.8	3.3	5.0	3.9	13	28
2/7/94	2.1	3.7	3.3	4.1	76	26
11/30/94	1.5	2.9	5.0	3.5	93	30

Our analysis indicates there is a significant difference in distribution of energy density between the empirical and JONSWAP spectra. Peak energy in the empirical spectrum is in the frequency range 0.15 Hz to 0.2 Hz, with the maximum 0.17 Hz. Maximum spectral energy for the JONSWAP spectrum is in the frequency range 0.2 Hz to 0.4 Hz, with the maximum 0.27 Hz. In addition, the empirical spectrum had multiple peaks, which could not be represented by the single-peak JONSWAP spectrum.

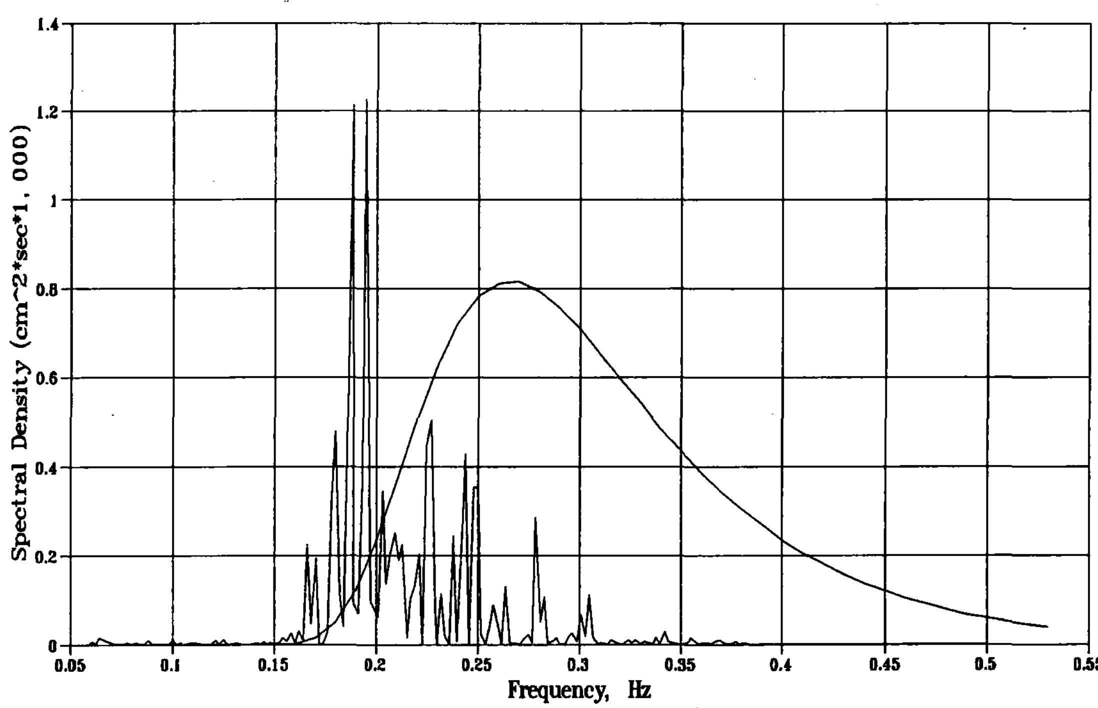

Figure 4. JONSWAP vs. empirical (Waverider data) spectrum 11/22/1993

DISCUSSION

- Comparison of recorded empirical and computed (hindcast) wave data in the vicinity of Elliott Bay indicated there are discrepancies between them. These discrepancies are seen at all locations for which data were available, but the magnitudes vary with site exposure, wind speed and direction. We have

not yet addressed this issue from a statistical point of view since only limited data were available for analysis.

- The significance of the discrepancy between measured and computed data should be considered when hindcasting waves at site until a comprehensive calibrated wave prediction model for Puget Sound is developed.

The example below points out the value of accurate knowledge of wave parameters in Elliott Bay.

Problem: In an Elliott Bay sediment recontamination study, it was unknown whether wind waves were responsible for suspension and transport of contaminated sediment near the waterfront properties.

Wave-generated bottom velocity was calculated for the Seattle waterfront at a depth of 20 feet (6.1 meters) MLLW using storm conditions of November 22, 1993. Significant wave height and period were developed from empirical data and hindcast procedures at the Waverider buoy location. Waves obtained by the two methods were transformed to a 20 ft depth in Elliott Bay for calculating bottom velocity.

Results:

- Measured waves—Bottom velocity is approximately 1.5 ft per second (45 cm per second);
- Hindcast waves—Bottom velocity is approximately 0.9 ft per second (30 cm per second).

Critical velocity for sediment suspension and transport in the study area was determined to be approximately 0.5 to 0.7 ft per second (15 to 21 cm per second). Therefore, actual data indicate the possibility of sediment suspension during extreme storm conditions.

The ACES computer model results do not recognize waves as a factor for sediment suspension and transport. However, if the wave contribution is not taken into consideration, the risk of future project failure could be significant.

The major problems that cause disagreement between measured and computed wave parameters are identified as irregularity of wind distribution and complicated geometry and topography of the shore. Most of Puget Sound has a more irregular and narrow fetch than other areas from which data were used in developing the ACES restricted fetch model (Smith, 1992).

Significant error in estimated wave height can result from inability to completely and accurately define and compare wind fields. The practice of using the wind statistics from Sea-Tac Airport because it is a long-term station may not be appropriate for many areas in Puget Sound. No standard procedure has been designed and verified to predict detailed wind and wave fields for particular storm conditions in Puget Sound.

The continued collection of wave data and analysis of historical data from previous studies would provide a unique opportunity to develop a reliable wind wave computation procedure for Puget Sound. The potential beneficiaries of such a project would be ports, marinas, government agencies (such as the U.S. Army Corps of Engineers and the state departments of Transportation, Marine Safety, Ecology, Fisheries and Wildlife), consulting engineering companies, homeowners, construction contractors, and others. The benefits of developing a Puget Sound wind wave computation procedure are:

- improved Puget Sound environmental control and monitoring ability;
- reduction of expenses for constructing and maintaining coastal structures (breakwaters, jetties, shore protection, marine facilities, etc); and
- improved quantitative assessment of performance level coastal structures, and risks in cargo vessel and ferry maneuvering and landing, and of the risk of spill and dispersal of oil and other hazardous materials in Puget Sound.

Minimum data (and thus funding) requirements for verification and operation of such a wave prediction model are (1) continued measurements by the Puget Sound Waverider in various selected locations, and (2) wind speed and direction measurements and real-time data reporting to a central computer.

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DETERMINATION OF EXCEEDANCE FREQUENCIES OF WAVE HEIGHT AND RUNUP IN PUGET SOUND

David P. Simpson[1]

INTRODUCTION

Economic investment in, and environmental consequences of, structural modifications made at the shoreline of Puget Sound emphasize the need for more precise estimation of the intensity of coastal processes, the elevations at which they act, and probability of their occurrence. Shore morphology, littoral drift, and effects of bulkheads have been subjects of other studies, but reliable information on the wave and runup processes that form the distinctive shore features have not previously been correlated to those features. A procedure was developed during a study of shore processes at Richmond Beach Park that has general applicability in Puget Sound for determining height of wave uprush on a beach and the associated frequency of occurrence. Results are of interest to:

- biologists for gaining a more quantitative understanding of interaction among elevation-dependent living resources, physical substrate, and hydrodynamic processes;
- designers wishing to refine design formulas for shore protection;
- planners establishing costs and comparable average annual benefits for construction at various elevations; and
- geomorphologists for understanding the frequency and magnitude of wave storms that create the zonation of the beach and backshore morphology.

PROJECT AREA

Richmond Beach Park, part of the King County Parks system, is located on the shore of Puget Sound between Seattle and Edmonds (Figure 1). The beach at the park currently experiences erosion of shore material by storm waves. The central portion of the beach area consists of a sandy area featuring a picnic shelter, restrooms and a concrete walkway that provides access from the upland parking area. King County Parks Department recognized the necessity of both halting erosion before nearby upland facilities were threatened and providing a solution that is compatible with the natural setting that is the focus of the park. Erosion that is causing concern takes place in the sandy area, which is above the mean higher

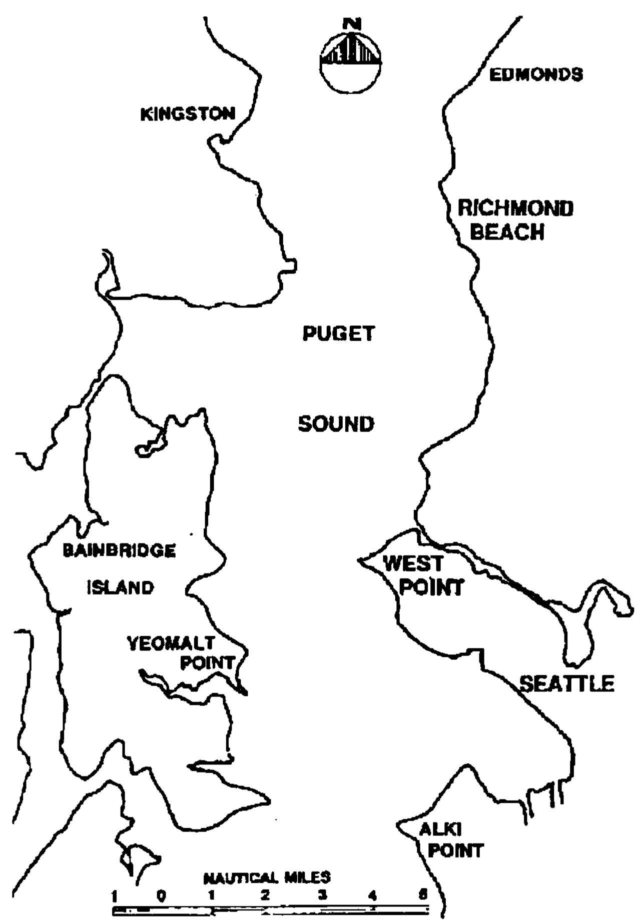

Figure 1. Central Puget Sound and Richmond Beach study area

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high water line. Sand is moved downslope by foot traffic toward the zone of occasional wave attack. Storm waves reaching shore at times of high tide remove some of this sand at the toe of the slope, leaving an erosional scarp. A natural gravel berm is present at the north end of the beach. Before shore protection could be designed, a study was needed for investigating causes of shore erosion at the site and documenting shore processes (Peratrovich, Nottingham & Drage, 1994).

The setting of Richmond Beach Park and the processes active there are typical of much of Puget Sound. Natural beach material at Richmond Beach is coarse-grained—up to gravel and cobble size. It is typically derived from bluffs that episodically release unsorted sediment to the swash zone. The resulting shore irregularity is usually temporary, contributing material to downdrift locations. Waves and currents alter the unsorted deposit by acting over different zones of the profile for various lengths of time and modifying the size composition as well as the shape of the deposit. The tide range, wave characteristics, particle size, and sediment supply rate act together to create a distinctive shape of the beach in cross section. Keuler (1979), in studying the foreshore character of northern Puget Sound, described the high tide beach/low tide terrace morphology. The high tide beach is a relatively steep beach face with coarse sediment. The low-tide terrace begins at the abrupt change in slope at the foot of the high-tide beach and contains poorly sorted fine-grained sediment. Factors contributing to this morphology include a large tidal range relative to the predominant wave height. Another is the differing response of gravel and sand to locally generated short-period storm waves. Gravel tends to be moved onshore and piled into ridges, while sand is winnowed from the upper foreshore and deposited in less turbulent water of the nearshore bottom.

PHYSICAL SETTING AND ENVIRONMENTAL PROCESSES

Tide and wind statistics applicable to Richmond Beach were collected and analyzed for occurrence frequencies. Wave characteristics were predicted using wind and fetch data. Wave runup was calculated using predicted wave height and period and surveyed beach profile. Occurrence frequencies of runup elevations were obtained by calculating the joint probabilities of occurrence of tidal elevations and of runup of waves having particular recurrence intervals. The methodology of analyzing each parameter and obtaining the runup occurrence frequencies is detailed below.

Tides

Puget Sound is subject to mixed tides, two tide cycles a day with diurnal inequality. Tidal currents are of moderate strength in the vicinity of Richmond Beach. The extent of beach profile that is alternately exposed and submerged in this mesotidal environment provides for valuable biological productivity. Tidal datums for Richmond Beach are listed below, referenced to the mean lower low water (MLLW) datum.

Highest Observed Tide	14.04
Mean Higher High Water	10.90
King County Aerial Survey Datum	6.56
National Geodetic Vertical Datum	5.89
Mean Lower Low Water	0.00
Lowest Observed Tide	-4.82

An exceedance frequency curve (Figure 2) of predicted tide levels for the site was developed from higher high water cumulative frequencies presented by Harris (1981, Table 41b) and methodology of the Corps of Engineers (USACE, 1989). Tide levels in the figure indicate the level of exposure the beach and backshore have to wave runup. High tide levels are important in terms of erosion potential when they are coincident with high wave events because deep water at the shore allows high waves to propagate closer to the backshore. It is assumed that major storms have durations that include at least one higher high tide.

Wind

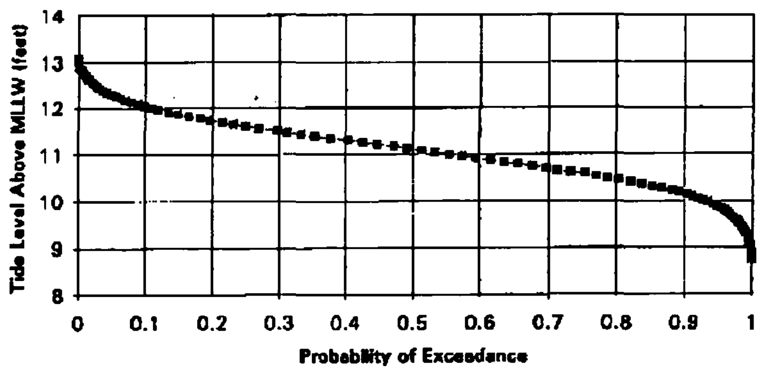


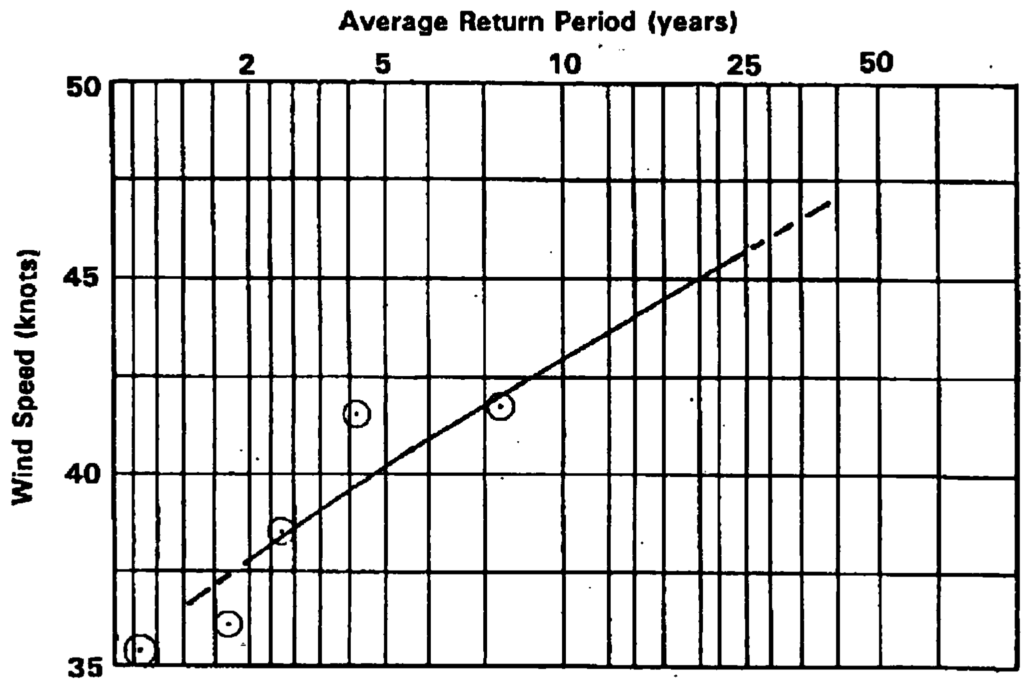
Figure 2. Exceedance frequencies of higher high tide levels, Richmond Beach

Regional topography causes a channeling of winds in primarily northerly and southerly directions at Richmond Beach, as in most areas of central and southern Puget Sound. Wind-generated waves arrive at the shore at oblique angles under most wind conditions because little refraction occurs in the relatively narrow, steep nearshore zone. These angles are strong factors in determining longshore sediment transport rates. Because fetches are short, transport rates are low by open-coast standards. Southerly winds are predominant in this portion of Puget Sound, and the resulting waves produce distinctive shapes of shoreline features, as the waves and beach attempt to establish a balance between form and process. One example is the asymmetric lobe defining the shore plan form at Richmond Beach.

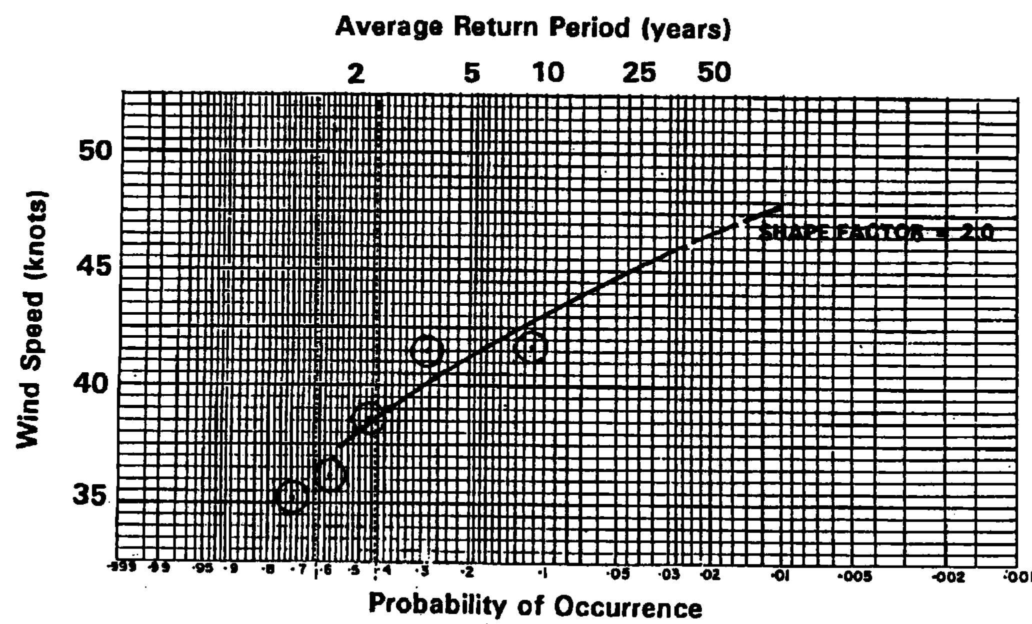
Summary wind velocity-duration information often used in the planning and design of structures on Puget Sound was developed by the Seattle District Corps of Engineers from wind measurements at Sea-Tac Airport and on Puget Sound (see Nelson and Broderick, 1986). Statistics from Sea-Tac are often used because that is a long-term station. However, wind speeds are usually greater on Puget Sound waters than at Sea-Tac. Although Sea-Tac winds are not directly applicable at Richmond Beach, those records contain relevant information about general wind characteristics. The fastest winds occur in the winter and are almost always from the south. Only twice since 1955 have the strongest winds in the winter been from the north. The monthly strongest winds are from the northerly directions more frequently in the spring and summer than in the winter, but southerly winds are still predominant in the record. Summer winds blow mostly from the north and northwest, and rarely at speeds that generate wave conditions of concern at Richmond Beach Park. Winter winds are mainly from the southwestern quadrant and generate waves that produce the predominant littoral transport.

Winds are measured at West Point, and those data are more applicable to wave predictions for Richmond Beach than are measurements at Sea-Tac. Digitized data from August 1967 through March 1973 are available from Puget Sound Air Pollution Control Authority. A computer program was written to read the time series of speeds and directions and summarize occurrences by 2-knot increments of speed and 16 points of the compass. Annual maxima of the one-hour average wind speeds for each point of the compass were also identified by the program for calculating recurrence intervals. Data from other sites are also available from that agency, and they could be easily analyzed for updating the standard Corps of Engineers wind velocity-duration curves for Puget Sound.

Estimates of wind speeds for recurrence intervals must take into account the type of distribution applied to the data, as well as the length of record. Estimates for return periods greater than 20 years have questionable reliability when the number of years of record are as few as in this case (seven years). Gumbel, Weibull, and log Pierson distributions are often applied to environmental data to estimate frequency and magnitude of events. The distribution to apply appears to be the one for which the observations most closely follow the theoretical distribution (Smith and Piggot, 1994). Plots of wind speed data using Gumbel and Weibull distributions are shown in Figure 3. The distribution having the best fit, and chosen to represent the exceedance frequency for West Point winds, is the log Pierson type III (Beard, 1962) and is shown in Figure 4a. By this analysis the 20-year recurrence interval wind speed for West Point is 46 knots from the south and 38 knots from the north.



(a) Gumbel distribution of annual maximum wind speeds at West Point. Correlation = 0.916.



(b) Weibull distribution of annual maximum wind speeds at West Point. Correlation = 0.933.

Figure 3. Extreme value distributions of annual maximum south winds at West Point

Geomorphology

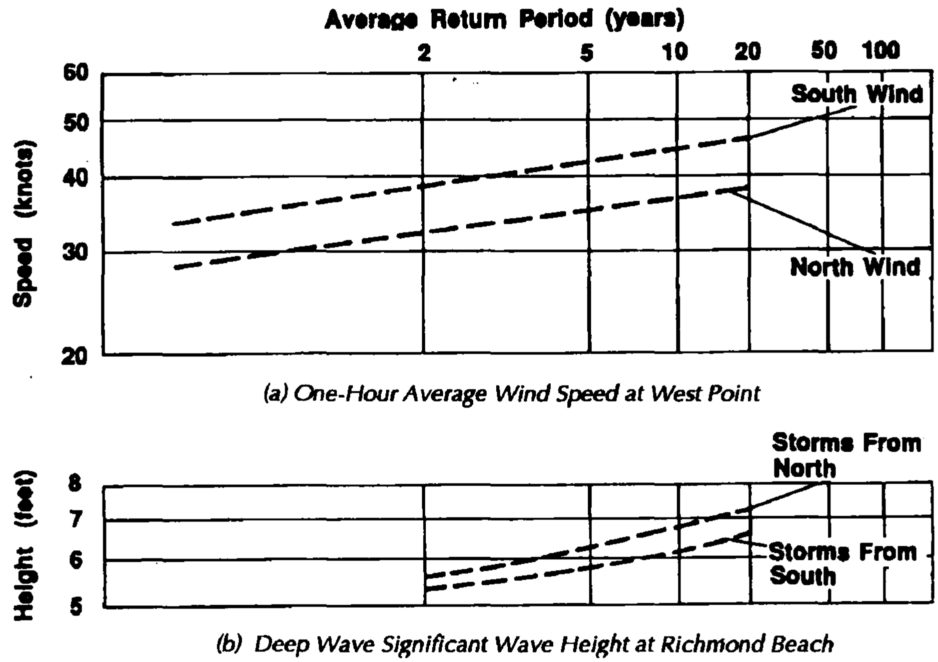


Figure 4. Wind speed and significant wave height exceedance frequencies, Richmond Beach

Beach materials and the dynamical form of the beach face attempt to reach an equilibrium with the prevailing wave energy reaching the shore. The result is a particular particle size distribution and beach shape, both in cross section and plan form. Where there is no long-term change in shape or dimensions of the beach, yet material is fluxing through the beach segment, that portion has attained stability. The gravel beach at the north end of the park is an example of a dynamically stable form throughout the beach profile. The central segment of the beach, facing southwest, exhibits loss of beach material from the upper slope. It results from downslope movement of sand from an unconsolidated mound. On occasions of high tide and high waves, it contributes a sufficient quantity of sand to the profile to affect swash hydraulics locally in the beach face and thus to interfere with the formation of a natural gravel berm. The higher proportion of fine grains in the beach material reduces percolation of the swash into the beach, which reduces the swash velocity asymmetry and thereby the net upslope movement of gravel, which is necessary for the protection of the backshore. Beach slope, a factor required for calculating wave runup, was determined from averaging survey data from six transects across the southwest-facing beach. The average slope of the profile in the surf zone is 8.2:1.

Because of the restricted fetch, waves rarely exceed 5 feet in height or 4½ seconds in period at Richmond Beach. Although the predominant wave angle has high obliquity to the general shoreline orientation (which is a factor for increased transport rates), longshore sediment transport rate is not high because of the coarse grain size and the limited supply of beach material. At Richmond Beach, the waves and sediment regime have produced an armored beach face. Sediment appears to be most dynamic in the upper portion of the beach profile (above mid-tide line). Predominant movement of sediment is to the north. Coarse material remains in the swash zone and is moved around the point at the north end of the park. Occurrences of high waves and high tide that cause erosion of the southwest-facing beach are relatively rare, but the removed sediment does not return by natural processes.

Waves

Wave predictions for the Richmond Beach location were made with wind data recorded at West Point, input to the Wind Adjustment and Wave Growth module of the Automated Coastal Engineering System (ACES) version 1.07b (Szuwalski, Leenknecht, and Sherlock, 1993). These computed wave characteristics are the basis for establishing the occurrence frequency of runup height at Richmond Beach and for examining the resistance of beach segments to storm wave erosion. The wave prediction procedure was

verified with measurements of winds and waves near West Point with the storm of November 22, 1993. Waves were measured with a Datawell Waverider buoy moored near West Point. It is funded by Washington Department of Ecology and the U.S. Army Corps of Engineers, and is part of the Coastal Data Information Program (CDIP). The ACES software hindcasted the significant wave height within 0.1 foot of the measured height during the storm peak. Although this one occasion for verification gave satisfactory results, the ACES wave model should be verified in other places in Puget Sound. More frequently reported wave parameters by the CDIP and more easily obtained wind data would be a great aid in verifying the wave model in a variety of conditions. Deploying Waverider buoys in other locations near anemometer stations would expand the verification of the model in Puget Sound.

Wave predictions were made using frequency of occurrence statistics developed from West Point wind data. Summary input and output of ACES are shown in Table 1. The significant wave heights corresponding to winds with given frequencies of occurrence are plotted in Figure 4b. The 20-year return-interval south wind is predicted to generate a 7.1-foot significant wave height in deep water near Richmond Beach. The corresponding spectral peak period is 5.2 seconds. The significant wave height, H_s (average of the highest one-third of the waves in a fully developed wave field), is the parameter of interest in the present analysis.

Table 1. Wind speed, wave height, and runup predictions at Richmond Beach

Return Period	1-Hour Wind (kt)	Significant Wave H (ft)	Peak Period	Runup R 1/3	Runup R10	Runup Rmax
South Winds						
2	38.0	5.5	4.7	5.0	6.2	8.1
5	41.5	6.2	4.9	5.6	5.9	9.1
10	43.5	6.6	5.1	6.0	7.3	9.6
20	46.0	7.1	5.3	6.4	7.9	10.3
North Winds						
2	32.0	5.2	4.7	4.8	5.9	7.8
5	34.5	5.7	4.9	5.3	6.5	8.5
10	36.0	6.1	5.0	5.6	6.8	9.0
20	38.0	6.5	5.1	5.9	7.3	9.6

As waves approach shore the shallow depths decrease the wave height and turn the wave direction to more shore-normal. A simplified method of calculating the refraction coefficient, the factor for reducing wave height, is presented in basic coastal engineering texts, such as the Shore Protection Manual (SPM, 1984). The refraction coefficient applicable to Richmond Beach was applied to deep water wave heights before calculating wave runup.

Wave Runup

Runup height is the vertical distance above the mean water level to which the uprushing wave reaches on a beach or structure; it is not referenced to a datum. Runup elevation is the level, measured from a datum, to which the wave reaches, and should be correlated to many biological and morphological features of the beach and backshore. Runup elevation is determined by the wave and beach characteristics and the mean water level on which waves are superimposed. In Puget Sound the mean water level is composed almost entirely of the tide height; such factors as surge and setup can be neglected.

Wave runup height was calculated by inputting wave heights (adjusted for refraction effects), wave periods of selected recurrence intervals, and beach slope to the ACES Irregular Wave Runup on Beaches

module. Computed runup heights were plotted on probability paper, as shown in Figure 5a.

JOINT PROBABILITY OF RUNUP AND TIDE

Wind wave generation and tide levels are assumed to be statistically independent. Significant runup to a certain elevation is the result of the joint occurrence of runup of a wave with deepwater height H_s and a particular tide level. The joint probability of the occurrence of tides and waves that would produce a particular runup elevation was determined by numerically integrating the probabilities of all combinations of runup and tide level that would sum to the given elevation. The joint probabilities for elevation increments were summed to form the cumulative distribution function, which is represented in Figure 5b.

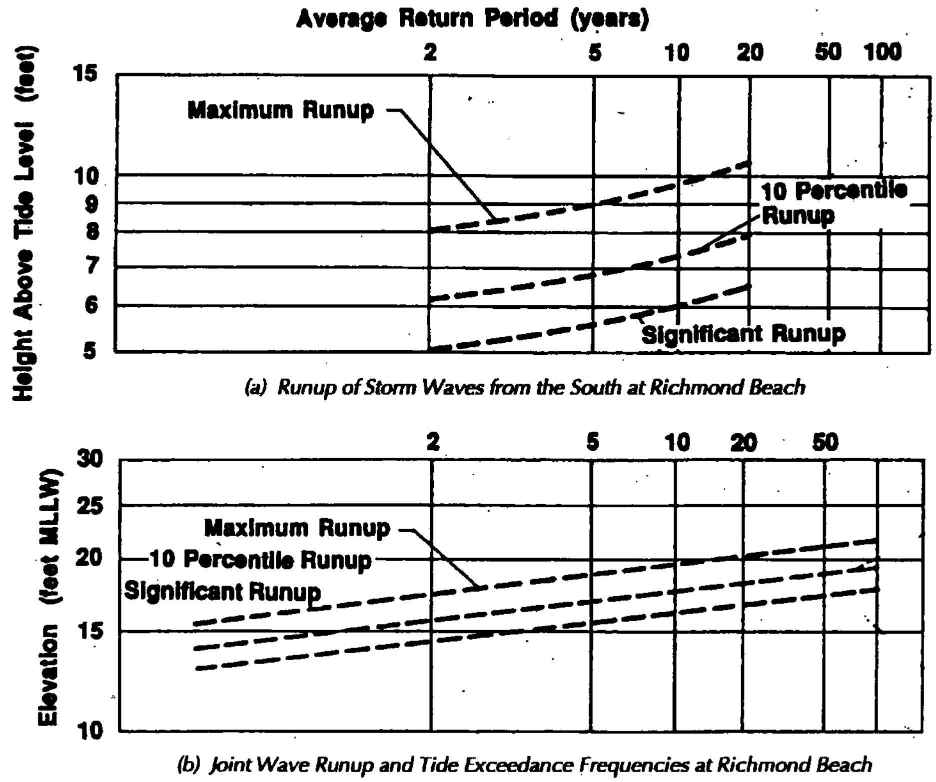


Figure 5. Wave runup exceedance frequencies at Richmond Beach

The probability distributions of tidal elevations and runup heights are continuous functions. The probability distribution may be described with the joint probability density function. Integrating the function over the applicable limits yields a volume under the surface defined by the joint probability density function and the ranges of runup height and tidal elevation that give the selected combined elevation (see Ang and Tang, 1975, p. 137).

An example of numerical approximation and integration follows. The runup elevation of 14 feet MLLW can be attained by an infinite number of combinations of significant runup ranging from 1 to 8 feet and tidal elevation ranging from 13 to 6 feet MLLW. The combinations are considered in 0.5-foot intervals, as a means of numerical approximation. The probability associated with any particular tide and runup combination is taken to be the midpoint of the probability density volume on either side of it. The average of all the individual volumes represents the probability of occurrence of all the combinations of runup and tide that produce a runup elevation of 14 feet MLLW. Similar calculations were made for runup elevations ranging from 13 feet to 18 feet MLLW. Their cumulative sums were plotted in Figure 5b.

DISCUSSION

Correlating beach and backshore features at Richmond Beach with computed runup magnitudes and occurrence frequencies is helpful in understanding the causal events that influence and maintain beach forms, habitat characteristics, and biological communities. The debris line on the eroding beach was at the toe of the sandy slope, and gives graphic evidence that runup is active at least to that elevation. That elevation is 13 feet MLLW (Figure 6). On the stable gravel beach at the north end of the park, the berm and drift log accumulation is at elevation 14½ feet MLLW. These elevations are reached by runup of the H_s wave annually. The 13-foot elevation of runup is reached more frequently than the 14½-foot elevation.

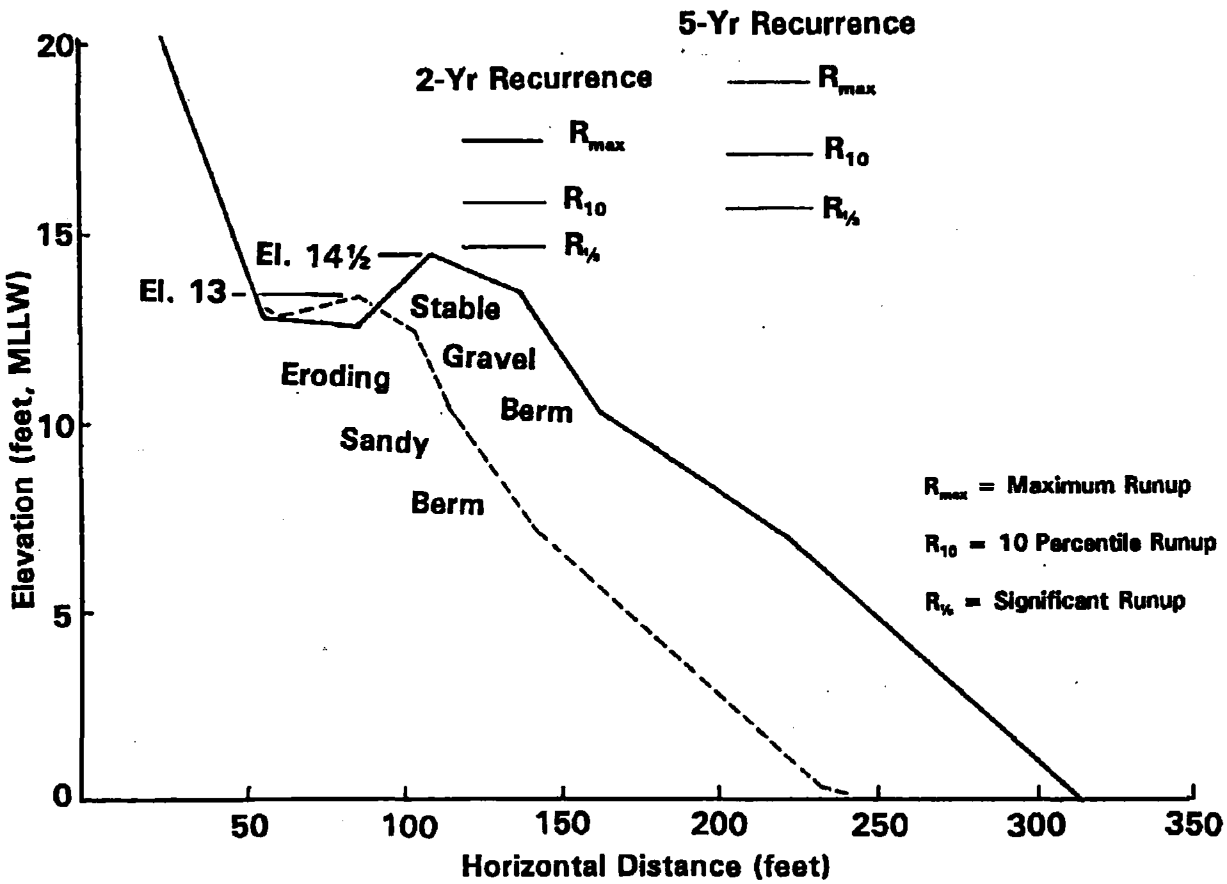


Figure 6. Beach profiles and tidal and runup elevations at Richmond Beach

Because the sand slope is actively adjusting to the erosion from wave runup, a berm has not yet formed at that reach of the shore. It is expected that the minimum height of a constructed protective berm for that location should be the same as that of the self-formed berm at the stable reach. Berm width is also an important factor in providing protection for the backshore. The flat or negative slope of the berm, as well as the vegetation and log debris on its surface, greatly diminish the runup height as it travels over the berm.

It could be speculated that a seawall placed above the elevation of some recurrence-interval significant runup might not interact with the beach and might not cause long-term beach changes. However, if the beach elevation at the toe of the wall is lowering because of a sediment deficit in the littoral stream, the structure would be exposed to runup with increasing frequency and might then exacerbate the profile lowering. Examples abound in Puget Sound where a scour trough is not present at the toe of a seawall. The elevation of the toe and the abundance of the sediment supply to the shore drift sector are obviously important factors in these examples. Performing the analysis described here for beach locations having various characteristics would expand our knowledge of the relationship between magnitude and frequency of energetic events and the morphological character of a shore site.

SUMMARY

A methodology was presented for determining the frequency of occurrence of wave runup elevations. The steps are (1) define tidal datums; (2) perform tide level analysis; (3) analyze wind speeds and

directions applicable to the fetch; (4) select the applicable probability distributions for wind speeds; (5) perform deep-water wave predictions for given wind speeds; (6) adjust wave heights for refraction effects; (7) calculate wave runup for the selected wave heights and periods; (8) combine runup and tide level through joint probabilities; and (9) field-check the results with beach morphology. The need exists for analyzing long-term wind information from Puget Sound shore stations and verifying a wave prediction technique for general locations in Puget Sound.

ACKNOWLEDGMENTS

The study on which this paper is based was funded by King County. The project manager for King County Facilities Management was Mike Lozano. Permission to publish these results is appreciated.

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SHORELINE ARMORING TRENDS IN THURSTON COUNTY, WASHINGTON: PROPERTY OWNER RESPONSES

Jacqueline Kettman[1]

RATIONALE

Throughout Thurston County's development booms of the last two decades, shoreline development permits boomed as well. The county recognized the need to better understand the cumulative impacts of the hundreds of parcel-by-parcel marine shoreline modifications that have taken place. Shoreline armoring has been the predominant factor in the incremental alteration of Thurston County's marine shorelines, as property owners respond to periodic landslides and the real or perceived threat to their property that these events represent. An inventory of Thurston County's shoreline armoring has the twofold purpose of enabling Thurston County to examine armoring trends, and producing data essential to the Coastal Erosion Management Strategy for Washington State (Canning, 1995).

OBJECTIVE

As the first study of its kind in Washington state, the Shoreline Armoring Inventory of Thurston County (Morrison, Kettman and Haug, 1993) also served as a "laboratory" in data development and integration. The Shoreline Armoring Inventory compared the extent of shoreline armoring between 1977 and 1992, evaluated armoring activity since 1985, assessed the accuracy of data gathering methods, and established a relational shoreline features database on a geographic information system (GIS).

GENERAL METHODOLOGY

All four study objectives were achieved through the development and use of the Thurston County Shoreline Features Database. The database was assembled from Thurston County shoreline permit files, Thurston County tax assessor parcel data, aerial photos from both 1977 and 1992, existing maps of shoreline features from the *Coastal Zone Atlas of Washington* (Ecology, 1980), and a boat survey of the county's marine shoreline. The portion of the shoreline within the city of Olympia was omitted from the study area, since it is largely developed with commercial and industrial uses, and the focus of this study was on residential armoring patterns. The data were integrated for maximum flexibility on an Arc/Info GIS.

The data produced for this study were developed by "relating" or connecting tabular data with the mapped data ("coverages" when used in a GIS). Figure 1 depicts how the data are connected within the Shoreline Features Database.

Although a variety of permits are required for shoreline developments, the data referred to as "Shoreline Armoring Permits" represent only county-granted Shoreline Act Administrative Exemptions (SAEs). SAEs require county staff review of the project proposal, and if granted, provide an exemption from Washington State Shoreline Management Act requirements that a shoreline substantial development permit be granted. Armoring projects generally do not qualify as substantial development projects. For ease of discussion, SAEs are referred to as "permits" even though their effect is to provide case-by-case exemptions to permit requirements. Data were collected onto standardized forms from county files and transferred to an R:Base computer database table.

The shore "line" that provides the fundamental data coverage to which all other data are connected was developed by modifying existing Thurston County assessor's maps to ensure shoreline segments of a minimum of about 20 feet in length.

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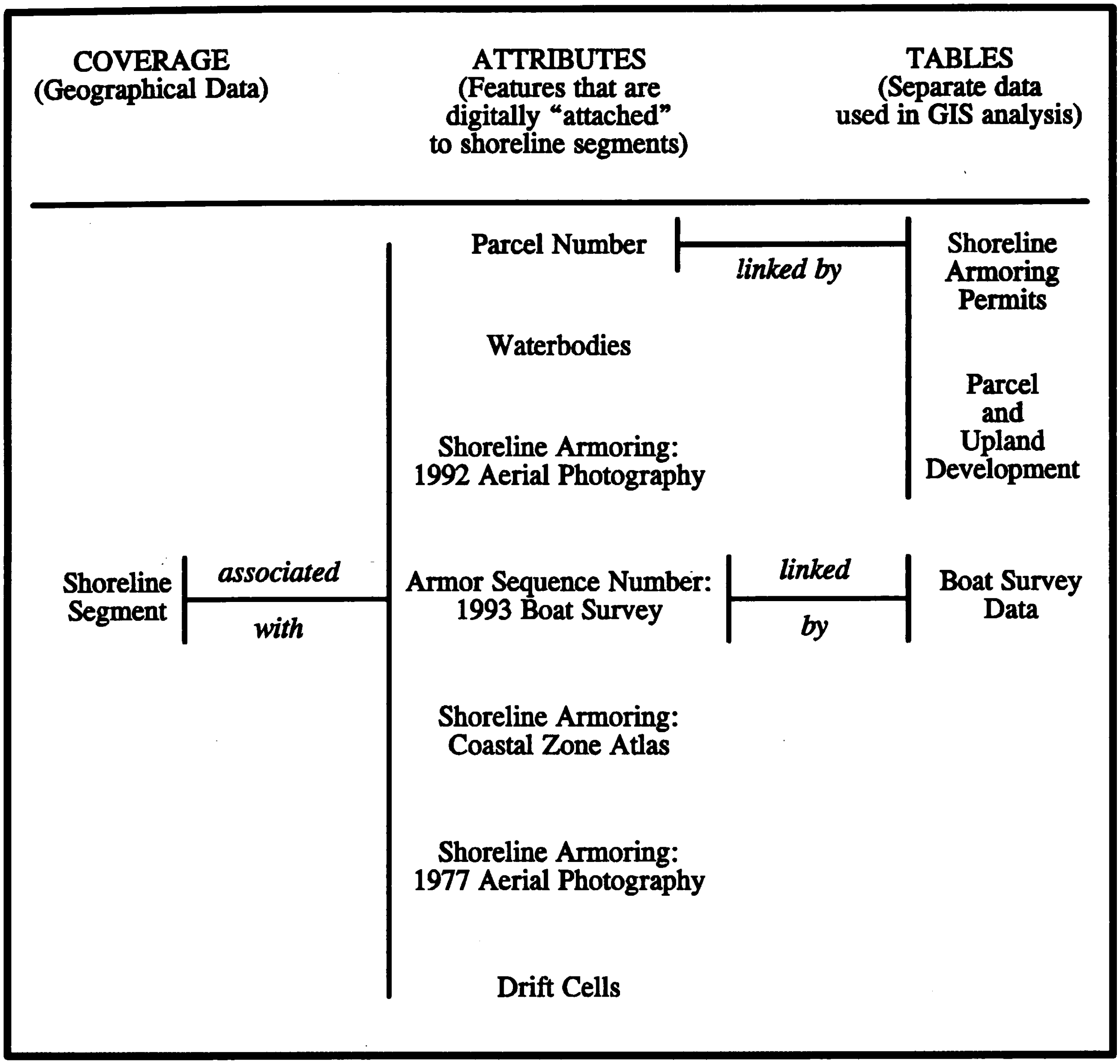

Figure 1. Thurston County Shoreline Features Database organization

Parcel and upland development data for shoreline properties within 200 feet of the shoreline were transferred from the Thurston County assessor's 1992 computer database to a smaller R:Base table. The assessor's tax parcel number provides a critical link between tabular and geographic data in the Shoreline Features Database. The assessor's 1992 parcel maps are one of the geographic coverages. Due to the discontinuity of parcel boundary shorelines in relation to geographic shorelines, some of the shoreline coverage's segments did not initially pass through parcel polygons. The GIS technician manually attached a parcel number attribute to the shoreline segment for parcels missed by the shoreline coverage.

Shoreline armoring data were compiled from four separate sources: 1) 1977 aerial photographs, 2) the *Coastal Zone Atlas* (Ecology, 1980), 3) 1992 aerial photographs, and 4) the January 1993 boat survey. Data were collected onto parcel maps for each set and later digitized into attributes to the GIS shoreline

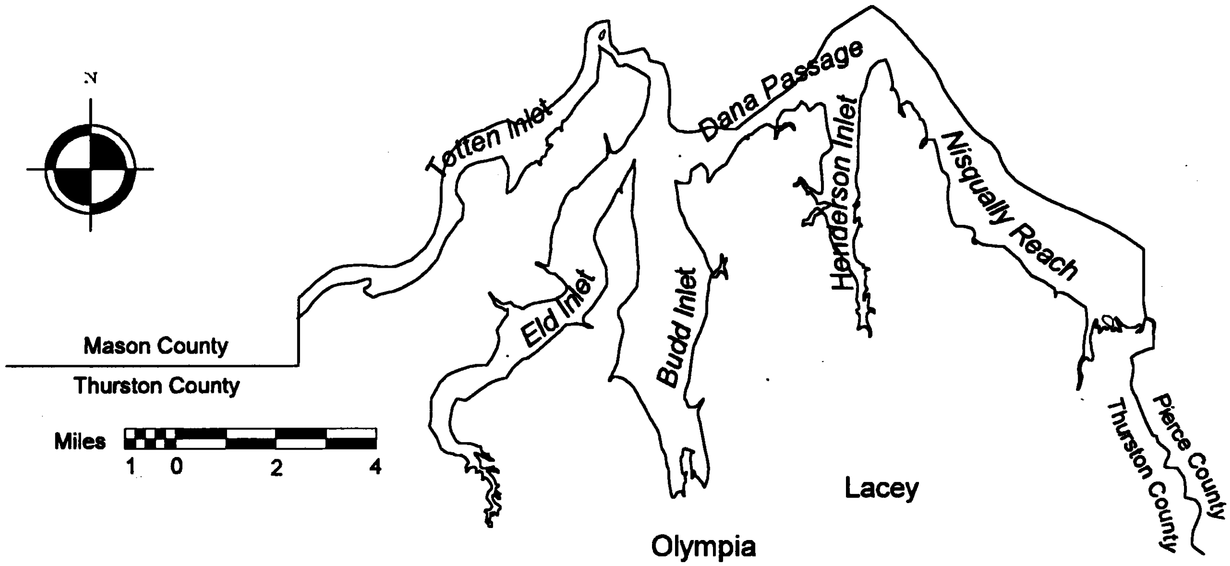

Figure 2. Thurston County shorelines showing inlets and reaches

coverage. The 1977 and 1992 aerial photo interpretation was conducted by separate staff to avoid potential bias in reporting.

The boat survey data were collected during several cold trips in January 1993. Each armor site was identified on a parcel map and assigned a sequential number. Various characteristics were recorded for each armor site, such as approximate length, condition, and construction type. The armor sequence numbers were digitized as an attribute to the shoreline coverage. The tabular data were transferred to an R:Base table, where they are linked to the shoreline coverage by the sequence number.

Additional attributes include "waterbodies" and drift cells. Using the waterbodies data, the shoreline is segmented by the four different inlets in Thurston County and by two broad "reaches" (Figure 2); this segmentation is useful in comparing intensively developed areas with more remote, rural areas. The drift cells data was originally developed with a ground survey (Hatfield, 1983). Although not analyzed for this study, the drift cell data, in combination with other shoreline features data, will enable future researchers to examine the status and potential impacts of shoreline modifications within each drift cell.

RESULTS

Methodology

Creating a GIS database for essentially linear features raised new issues for data organization: polygonal data had to relate to linear data; layering data on a line was cost-efficient, but it hampered map analysis. Operator error during the digitizing resulted in the data corruption of the beach materials coverage (from the *Coastal Zone Atlas*). Mismatching mapping-coordinate systems precluded using an existing soils coverage, which would have been useful for identifying steep slope areas.

Data Comparison

Data from 1992 aerial photograph interpretation were compared to data from the January 1993 boat survey. The aerial photograph data included 96 false positive reports of shoreline armoring and 326 false negative reports of armoring, comprising an overall error rate of approximately 34 percent.

In addition, 1977 aerial photograph interpretation data and mapped data from the *Coastal Zone Atlas* (Ecology, 1980) were compared with 1993 boat survey data. From the 1977 aerial photographs, 24 percent

of the positive responses could not be confirmed by the 1993 boat data, suggesting false positives; from the *Coastal Zone Atlas*, 27 percent of the positive reports could not be confirmed.

Armoring Trends

The 1993 boat survey data reveal that approximately one-third of Thurston County's marine shoreline is armored. The amount of armored shoreline roughly doubled in 15 years. Table 1 shows the increase in shoreline armoring throughout six segments of the Thurston County shoreline.

Table 1. Shoreline armoring: 1977 – 1993

	Budd Inlet	Dana Passage	Eld Inlet	Henderson Inlet	Nisqually Reach	Totten Inlet	Total
Parcels Armored in 1977	217	27	313	104	69	86	816
Parcels Armored in 1993	330	86	559	164	171	139	1,449
Number Change	113	59	246	60	102	53	633
Percent Change	52%	219%	79%	58%	148%	62%	78%
Shoreline Length Armored in 1977, Feet	20,735	2,767	29,977	9,996	5,970	6,604	76,049
Shoreline Length Armored in 1993	34,108	8,485	29,977	19,177	19,594	14,388	159,453
Number Change	13,373	5,718	33,724	9,181	13,624	7,784	83,404
Percent Change	65%	207%	113%	92%	228%	118%	110%

In recent years about two-thirds of the permits issued for armoring were for replacement projects. Still, on average, each year an additional half mile of Puget Sound shoreline armoring was permitted in Thurston County alone between 1985 and 1992. An average of 1.2 miles of replacement shoreline armoring was permitted per year.

The rate of new armoring construction outpaced the rate of residential construction along the marine shoreline by 42 percent during the period studied. Less than half the marine shoreline (42 percent) had no upland development or armoring in 1993.

CONCLUSIONS

The rate of marine shoreline armoring in Thurston County is significant, and monitoring should continue. Any impacts will be difficult to mitigate or reduce in highly urbanized portions of the county. Future trend studies can be designed to address priority impact risk factors, based on emerging information about biological impacts.

POLICY IMPLICATIONS

One relatively undeveloped inlet in the county, Totten Inlet, may yet benefit from the CEMS project. The shoreline features database could be further developed with little effort to enable the county staff and the public to assess the potential impacts of shoreline armoring within the context of the site's drift cell and other site conditions.

ACKNOWLEDGMENTS

The study discussed in this report was funded through a cooperative agreement with the National Oceanic and Atmospheric Administration, grant number G9300030.

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SHORELINE ARMORING EFFECTS ON PHYSICAL COASTAL PROCESSES IN PUGET SOUND

Keith B. Macdonald[1]

INTRODUCTION

Shoreline erosion is a less serious problem within Puget Sound than along the outer coast. Despite this, coastal erosion structures such as concrete, rock, and timber bulkheads are common around the Sound (Downing, 1983; Morrison et al., 1993). Shoreline property owners often view such armoring as critical for real estate protection, while resource managers are concerned about potential impacts on nearshore marine fish and shellfish habitats.

In 1992, Washington Department of Ecology (Ecology) initiated a three-year interdisciplinary study of the effects of widespread shoreline armoring to support development of a Comprehensive Erosion Management Strategy for greater Puget Sound (Canning and Shipman, 1994). This paper summarizes the results of one element of the study: the effects of shoreline armoring on physical coastal processes in Puget Sound.

METHODOLOGY

This study is based on review and synthesis of information drawn from three complementary sources: (1) a comprehensive literature search; (2) discussions with regional specialists concerned with the design, installation, and impacts of shoreline armoring; and (3) Puget Sound case studies.

The literature search identified numerous national and foreign publications on shoreline armoring, but most describe seawalls in sandy beach settings on open-ocean coasts. Publications dealing specifically with Puget Sound, or with semiprotected estuarine beaches more like those of Puget Sound (Nordstrom, 1992; Terich et al., 1994), remain scarce. The bluffed bays of the East Coast, specifically the Delaware and Chesapeake shorelines (Shorelines Inc., 1992), and several Great Lakes shorelines (O'Neill, 1986; Keillor and Miller, 1987; SEWRPC, 1988) offer the best models for comparison.

Regional specialists contacted included representatives from Ecology (D. Canning, H. Shipman, and P. Skowland) and the Washington Department of Fisheries (K. Bates and N. Rickard), the University of Washington School of Oceanography (R. Sternberg), Western Washington University (M. Schwartz and T. Terich), the Army Corps of Engineers, Seattle District (E. Nelson), Battelle Northwest (J. Downing and R. Thom), local consultant Wolf Bauer, and CH2M HILL (D. Simpson, B. Paulson, J. Cox, and J. Gendron). A telephone survey of Puget Sound's County shoreline planners was also conducted.

The original goal of the case studies was to identify Puget Sound sites where armoring-related physical shoreline impacts and secondary biological effects have been quantitatively documented. The regional specialists quickly confirmed, however, that only one site—Lincoln Park Beach in Seattle—really meets these criteria. Sufficient data are available at a few additional sites to develop chronological site histories and quantify some of the more obvious physical impacts resulting from shoreline armoring.

BACKGROUND

Natural Shoreline Processes

Puget Sound shorelines strongly reflect the region's recent glaciation. The Sound's channels are deep, narrow, and steep-sided. Except for depositional rivermouth settings (Burns, 1985), much of the shore is characterized by steep glacial-till bluffs, fronted by narrow beaches and low-tide terraces that rapidly drop off into deep water. Unlike ocean beaches that usually consist of river-borne sands, the source material for

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most Puget Sound beaches comes from wave erosion and episodic slumping of the glacial-till bluffs (Keuler, 1979; Downing, 1983).

The narrow channels and limited fetch typical of Puget Sound result in short-period storm waves that sort and winnow the slumped till material, piling the coarser gravel into beach ridges while carrying the finer sands and silts to the lower foreshore. The Sound's large tidal range (the daily range is eight feet at Port Townsend, 15 feet at Olympia) relative to the smaller predominant wave height is also an important control on beach morphology (Nordstrom, 1992). Seasonal changes in wind direction and wave approach control sediment transport along the shore (littoral drift; Schwartz et al., 1989), while changes in wave height move beach material onshore (summer depositional profile) and offshore (winter erosional profile).

The major components of the shoreline—bluffs, beach, and nearshore zone—are linked by important physical processes (functional linkages) and can be understood and successfully managed only as a single dynamic unit. Throughout much of the Sound, bluff erosion is an important natural process that is critical to maintaining an adequate supply of new sedimentary material to the beach below. If this supply is cut off, continuing wave action and littoral drift can be expected to result in local beach loss and eventually accelerated local bluff retreat. Placement of shoreline armoring can disrupt natural linkages between bluff and beach processes, sometimes with serious physical and biological consequences.

Drift Sectors

Littoral drift carries sediments along Puget Sound beaches between "source" and "sink" areas that respectively mark the beginning and end of discrete drift sectors (littoral or transport cells; Figure 1). While open coast littoral cells extend for miles between river-mouth sources and submarine canyon sinks (Komar, 1976), the irregular Puget Sound coastline results in hundreds of much smaller drift sectors. Puget Sound source areas are typically "feeder bluffs," from which material periodically slumps to the beach (temporarily protecting the bluff tow from further wave erosion). Waves and alongshore currents sort this material, transporting it downdrift (i.e., via driftway) toward a sink—usually an accreting feature such as a barrier beach, sandbar, spit, or cuspate foreland. Placement of shoreline armoring at the toe of a feeder bluff will clearly have different consequences from those of placing the same structure behind an accretionary beach (Terich, 1987; Schwartz et al., 1989; Shipman, 1993).

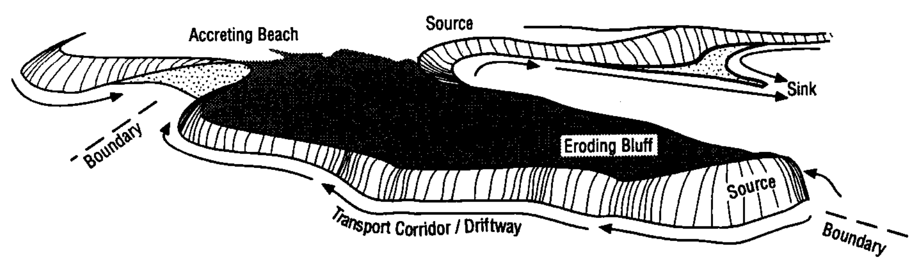

Figure 1. Shoreline drift sectors: source (feeder bluffs), driftway and sink (accretionary beaches)

Hard Versus Soft Armoring

Shoreline erosion control has traditionally been accomplished by "hard" armoring—construction of erosion-resistant barriers along the shore to stop the land from retreating. The most common applications for residential properties around Puget Sound are poured-concrete bulkheads and near-vertical placed-rock walls. Less frequently encountered hard structures include log, plank, and sheetpile bulkheads, stepped and recurved seawalls, riprap and revetments (Downing, 1983; Morrison et al., 1993; Cox et al., 1994). All of these structures attempt to stop erosion by deflecting or dissipating the erosive energy of breaking waves.

More recently, recognition that the beach itself is a highly effective wave attenuator has focused interest on "soft" solutions. Soft solutions include dynamically acting or compliant approaches, in which sediments move continuously to achieve dynamic equilibrium with local waves and currents. Examples include beach nourishment with sand or gravel fills, creation of new beaches and beach strands, bluff and beachface dewatering and drainage controls, and vegetation management for shoreline and bluff stabilization (Davison et al., 1992; Menashe, 1993; Myers Biodynamics, 1993; Cox et al., 1994).

LITERATURE REVIEW RESULTS

Literature review results confirm that shoreline armoring can cause a variety of direct, indirect, and cumulative impacts on physical coastal processes in Puget Sound (Table 1). Direct impacts include excavation and burial effects from the placement of structures along the shore—be they beachfills (nourishment), rock revetments, or concrete bulkheads—as well as all the temporary impacts associated with their construction (noise, vibration, increased turbidity, work barge impacts, accidental spills, etc.). Depending on their placement relative to the natural shoreline, addition of structures is likely to result in a direct loss of beach area and narrowing of the sediment transport corridor (driftway).

Table 1. Shoreline armoring impacts on physical processes

- Direct Impacts
  - Construction Impacts
  - Loss of Beach Area due to Placement of Structures
  - Impoundment (Loss) of Sediment Source Behind Structures
- Indirect Impacts
  - Downdrift Impacts from Sediment Impoundment
  - Hydraulic Impacts from Armoring
    - Increased Turbulence/Erosional Energy Seaward of Armoring
    - Dry Beach Narrowing/End Wall Effects
    - Beach Profile Lowering/Steepening
    - Substrate Winnowing/Coarsening
    - Loss of Organic Debris (inc. LOD)
  - Modifications of Groundwater Regime
- Cumulative Impacts
  - Incremental Increases in All Impacts
  - Impacts to Single Drift Sectors
  - Potential Threshold Effects

Sediment Impoundment

Impoundment of beach sediments (behind a bulkhead or updrift of a groin) or upland sediment sources that would otherwise be available to feed adjacent and downdrift beaches is the most widely acknowledged, least controversial, and probably most significant effect of installing shore protection structures (Everts, 1985; Dean, 1986; Tait and Griggs, 1991; Griggs et al., 1994).

Shore armoring impacts are site-specific, varying with site geology (landforms and sediment type), local wave energy regime, and the type of shore protection installed. Three additional variables help determine sediment impoundment impacts: (1) the long-term trend in regional shoreline position: impoundment will accelerate retreat of an already regionally retreating shoreline, but will affect regionally stable or accreting shores only during major storm events; (2) the location of the armoring within the beach profile, which controls the frequency of interaction with waves and currents, and thus the potential for

modifying sediment transport; and (3) the existing beach width and local sediment supply—for as these diminish, sediment impoundment impacts will increase (Sato, Tanaka and Irie, 1969; McDonald and Patterson, 1985; Griggs, 1987; Kraus, 1988).

Sediment impoundment landward of mean higher high tide (MHHW) is unlikely to result in beach impacts except under unusually high water and severe storm conditions. At such times the "unavailability" of the impounded material can lead to rapid beach erosion. Impoundment of sediment sources at progressively lower elevations across the beach profile results in increasing "shortfalls" in longshore sediment transport required to maintain an equilibrium beach profile. Erosion will increase, both immediately in front of the shore protection, and at downdrift locations, and the beach front will retreat.

Both hard and soft shore protection act to impound sediments and sediment sources that might otherwise supply local longshore transport needs. Soft solutions, if designed to incorporate "sacrificial" fill, can partly offset impounded sediment losses and thus reduce potential impacts.

Quantitative data relating source impoundment to downdrift beach erosion are available for Ediz Hook, Port Angeles (U.S. Army Corps of Engineers, 1971; Galster and Schwartz, 1990) and the Siletz littoral cell on the central Oregon Coast (Good, 1992). Quantitative studies of a Lake Michigan beach/seawall system (Kraus, 1988) concluded that the volume of material eroded from the unprotected beach downdrift of a 580 m-long seawall was approximately equal to that removed from the sediment transport corridor by impoundment behind the wall. Construction (1961) and subsequent removal (1980) of a sludge lagoon at West Point, Seattle, created hard shoreline armoring that was in place only 20 years. The structure sharply interrupted littoral drift along a previously stable shoreline. Sediment accretion occurred as far as 750 feet updrift from the armored shore segment, while significant erosion was measured for about 260 feet (30 percent of the revetment length) downdrift of the armoring. Following revetment removal in 1980, the shoreline was restored to its former condition with a "soft armoring" gravel beach fill (Domenowske, 1987).

Hydraulic Impacts

Hydraulic impacts of armoring on physical coastal processes are caused by interactions of the armoring with waves and sediment (Weggel, 1988). Observations of net removal of beach sediments fronting armoring located waterward of MHHW are in marked contrast with the minimum impacts of armoring placed higher up the shore (Berrigan, 1985; Wiegel, 1992; Plant and Griggs, 1992). Two different mechanisms have been cited to explain this beach loss. It is widely stated that hard shore protection reflects wave energy back into the breaker zone, increasing water oscillation and turbulence in front of the armoring, and particularly at the toe of the armoring (Kraus, 1988). This reflected energy mobilizes both finer suspended and coarser bedload sediments, making them available for transport out of the area.

An alternative explanation suggests that the beach profile seaward of armoring does not depend on the presence of the armoring but rather on the amount of sediment available to form the profile (Dean, 1986). Large waves reaching shore require a broad surf zone to dissipate incident wave energy. If adequate beach material is available, the waves will create a beach profile with dimensions that provide for uniform energy dissipation across the surf zone during a storm event. If beach material is inaccessible because it is impounded, storm waves will attempt to "borrow" the necessary beach material from another unprotected location. The amount of material borrowed depends on the wave height that alters the profile and the amount of material impounded. After the storm event, in a climate of constructive waves, if the redistributed material is still in the shoreline reach, the profile will again be remolded to provide for the required energy dissipation rate. If the material is inaccessible, however, the profile will remain altered permanently. Whichever mechanism predominates, several important hydraulic impacts on shoreline processes are documented in the literature (Table 1).

Dry Beach Narrowing and End Wall Effects

It is important to distinguish beach narrowing resulting from regional shoreline erosion and retreat from narrowing resulting from hydraulic impacts of shore armoring. Beach narrowing in front of shoreline

armoring, and related end wall effects, are the most widely accepted, best documented hydraulic impacts caused by armoring (Smith and Chapman, 1982; Tait and Griggs, 1991). Beach narrowing in front of armoring is common in Puget Sound. Generally coarser beach sediments and lower wave energy may minimize impacts, but severe winter storms, such as seen in 1990-1991, can cause serious episodic impacts.

Armoring located waterward of MHHW will cause increasing impacts as armoring, waves, and sediments interact more frequently at successively lower elevations across the beach. Kraus (1988) predicts maximum net erosion when the seawall is located about three-fifths of the distance from wave breakpoint to the still-water line. Increasingly reflective armoring (e.g., smooth vertical bulkheads and seawalls) will have a greater impact and result in more pronounced beach narrowing than less reflective shore protection (e.g., sloped rock revetments or gravel beach nourishment). At the toe of reflective faces, the structure and beach material are exposed to larger hydraulic forces. Toe scour is a common cause of failure for seawalls (USACOE, 1981; Silvester and Hsu, 1993).

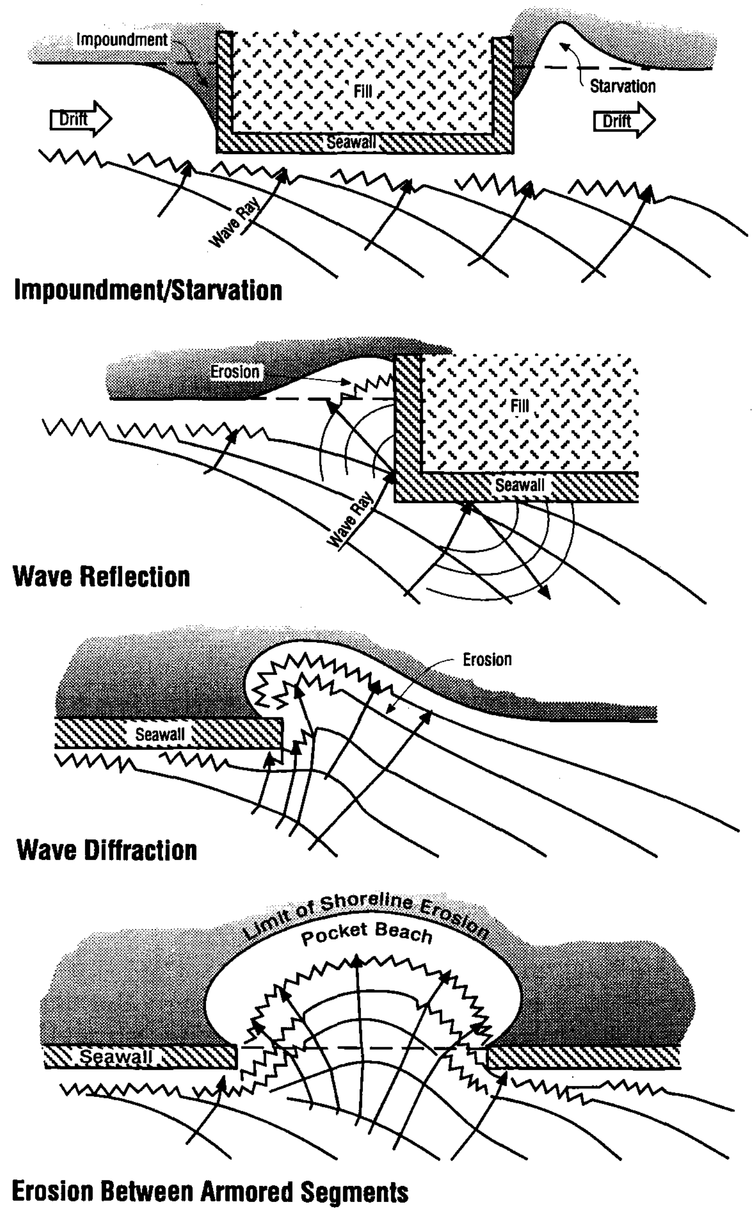

Figure 2. End wall effects

End wall effects—in which shore protection juts onto the beach waterward of MHHW and behaves like a groin—can cause significant additional beach erosion (Figure 2). Waves reflected from such end and return walls (anchoring armoring to the adjacent upland) can be directed to the adjacent beach and reinforce incoming waves, resulting in increased transport and erosion. Abrupt corners and ends of armoring also form defracting points, causing wave crests to radiate outward from the point (Figure 2). Crests that strike the adjacent beach can cause localized shore erosion similar to that from reflected waves. Studies of the geometric form of headlands and bays (Hsu et al., 1989; Silvester and Hsu, 1993) show striking parallels with wave response to discontinuous shore armoring. Shoreline retreat within a gap will

not exceed 30 percent of the gap distance between adjacent armoring sections for uniform sediments and most reasonable angles of wave approach (Figure 2).

A quantitative relationship between length of shoreline armoring and length of downdrift erosion (i.e., latter equals 70 percent of former; McDougal et al., 1987) has been postulated, but has not been widely tested nor generally accepted. Another quantitative relationship (Dean, 1986) suggests that the volume of sediment scoured in front of a seawall equals 60 percent of the "upland" volume that would have been eroded in the absence of the seawall. This too remains to be adequately tested.

Soft solutions, particularly beach nourishment, can minimize the potential for beach narrowing. Such approaches do not present reflecting surfaces or diffraction points to the waves, and the nourishment material itself can increase sediment supply to the littoral transport system.

Beach Profile Lowering and Steepening

Field observations (Tait and Griggs, 1991) indicate that the scouring of a trough locally in front of a seawall high in the beach profile occurs in response to large storm waves and that the beach sometimes recovers. Monitoring at Monterey Bay (Griggs and Tait, 1988; Griggs et al., 1994) showed that with the onset of erosive winter wave conditions, but before the waves had reached the seawalls, the beach was initially cut back uniformly alongshore. Profile lowering began when waves reached the wall. The wide summer berm in front of the wall was eroded sooner due to scour from reflected waves. The contours of the beach face migrated landward in front of the wall, while the berm profile persisted seaward of the position of the wall on the adjacent natural beach.

If armoring is placed on a retreating shoreline, even initially landward of MHHW, the beach profile will eventually lower to the point where waves will reach the armoring. A regionally retreating shoreline is starved of beach material. There is insufficient material to maintain the equilibrium profile, it translates shoreward, and depth increases at a fixed location. Few locations in Puget Sound have an abundance of beach material. It is usually at the location where individual bulkheads are constructed that the effects of sediment starvation are manifested. The lowering of beach levels (up to 3 feet or more) observed in front of some Puget Sound armoring (Shipman and Canning, 1993) reflects decades of landward translation of a sloping beach profile, rather than the impact of any single storm event. Similar localized deepening due to profile irrigation is described by Dean (1991).

FitzGerald (1980) and FitzGerald et al. (1981) describe a Massachusetts beach response to an intense February 1978 storm. A beach backed by a seawall showed general profile trends of accretion where gravel predominated and erosion where sand predominated. This illustrates the difference in the behavior of sandy beaches and gravelly beaches under similar wave conditions, and qualifies conclusions drawn from studies of sandy beaches. The gravel content in high tide beaches of Puget Sound is important to maintaining the beach width and protecting the bluffs.

Soft shore protection does not cause local deepening of the beach profile as its function is generally to fill the profile with placed material. Widening a sloping beach also increases the elevation of the beach, which has important benefits for protection against wave runup.

Substrate Coarsening

A longshore current, flowing near the toe of shore armoring, is not expected by itself to sort or transport larger particles of the size found on most Puget Sound beaches. Wave forces and turbulence generated during wave breaking would move beach material, through a combination of (finer) suspended load and (coarser) bedload transport. Once suspended in the water column, even if for a very short time, the smaller particles would be translated (winnowed) with the main current. Where wave breaking is induced by shore armoring, or where structures are located so as to be struck by breaking waves, the substrate could thus be modified to coarser sizes.

Field observations by Puget Sound Fisheries staff suggest storm-related turbulence close to armoring may result in winnowing and settlement of sand and pea gravel that mimics ideal spawning habitat for some fish species. Without the armoring and added turbulence, the pea gravel would provide a stable

habitat for egg laying and larval fish development. With armoring, however, subsequent storm waves will resuspend and re-sort the pea gravels, destroying any fish eggs present. No quantitative verification of these observations is available to date.

Kraus et al. (1988) analyzed survey data from a 12-mile stretch of New Jersey coast protected by a rubble seawall. Individual profiles dated 1953 and 1985 were compared with the "equilibrium profile" described by Dean (1977). The comparison suggests that a seawall-backed beach profile tends to be in equilibrium with the coarser grain sizes comprising the beach sediment. This implies that a lower profile develops in front of shore armoring after installation than was present before armoring. It might also mean that the beach retains only the coarser fraction in front of the armoring, consistent with the idea of greater size-ability of combined incident and reflected waves to move sediment particles and the winnowing of sand from the beach material fronting the armoring.

Beach nourishment can cause coarsening of the substrate directly by the placement of coarser material to offer greater protection. Such was the intent of constructing a gravel-cobble beach on a rapidly retreated shore of Flathead Lake, Montana, to stabilize the shore for protection of adjacent wetland and upland habitat (Da Costa, Scott, and Simpson, 1992).

Loss of Large Organic Debris

Large organic debris (LOD) can take the form of beached logs that have floated to a site as well as living or dead vegetation that falls on the back beach throughout the year or is contributed by slope failure or soil creep. Historically, the most significant role of LOD—especially the massive accumulations of drift logs and stumps at river mounts, backshores, and bluff toes—was the protection of these locations from excess wave and current action, and thus the slowing of local erosion (Stembridge, 1979). Large organic debris also forms both a microhabitat and food source that is a very important in the overall shoreline food web (Maser et al., 1988; Thom et al., 1994).

LOD can be prevented from accumulating at a site if the beach is too steep, or the profile is too low for LOD to become beached. To the extent that profile steepening and lowering can be attributed to hard shore armoring, armoring can cause loss of LOD. Land clearing and bluff modifications, while not caused by shore armoring, are often associated with it, and also can result in declining organic inputs (Macdonald and Witek, 1994). Soft shore protection solutions, by their nature, provide a beach at least temporarily. Where the profile has been remolded by wave action, a slope is produced conducive to beaching of floating debris. An exception is if the beach fill is of such coarse material and the waves so energetic that a very steep slope naturally develops.

Modification of Groundwater Regime

Installation of low-permeability armoring high on the beach can result in modification of local groundwater conditions that in turn affect the beach. Increasing pore pressure in beach sands, for example, tends to "fluidize" the sand, making erosion and transport easier (Waddel, 1976, 1980). Monitoring groundwater elevations and beach swash mechanics in front of seawalls and at unarmored locations in Monterey Bay, California, Plant and Griggs (1992) found higher water tables in beaches backed by seawalls. The higher water tables reduced infiltration into the beach from uprushing waves, causing an increase in downrushing (erosive) sheet flow. This caused an adjustment to coarser sediment, a steeper profile with a more landward shore position, and a quicker change from summer to winter beach profiles along armored versus unarmored shorelines. This impact has not been studied in Puget Sound and may be less significant for local coarse-sediment beaches.

Modification of groundwater regime plays a well documented role in the stability of banks and bluffs that supply sediment to Puget Sound beaches (Tubbs, 1975; Macdonald and Witeck, 1994). Fisheries staff (K. Bates, N. Richard, 1993) also note the importance of maintaining hydraulic and hydrologic continuity where accretionary beaches separate marsh/wetland habitats from the Sound (Shipman, 1993).

Impact by Shore Protection Method

While there is extensive engineering literature on the structural design (storm-worthiness) and effectiveness of different shore protection methods, the physical and ecological impacts of shore protection on coastal zone processes and habitats are rarely addressed (Tait and Griggs, 1991; Nordstrom, 1992). No systematic, quantitative studies relating various shore protection methods to specific levels of beach or shoreline impact have been identified. Studies such as Tait and Griggs (1991) and Smith and Chapman (1982, on boulder revetment walls) represent an important beginning.

Despite scarce quantitative data, the literature indicates broad agreement that different impacts among shore protection methods result largely from differences in the efficiency with which they either absorb and dissipate incoming wave energy or reflect it back out into the nearshore zone. At one extreme, a long stretch of undisturbed sand beach—its slope in natural equilibrium with local wave conditions—dissipates incoming wave energy highly efficiently. Little or no energy is reflected back offshore, and beach impacts are minimal. At the other extreme, a smooth-faced, recurved, concrete seawall, extending into intertidal depths, can reflect almost all of the energy from incoming waves back into the nearshore zone, resulting in substantial hydraulic impacts.

Impact by Location Within Drift Sector

Differences in the location of an armored shoreline site within a drift sector are also likely to result in different levels of impact. While no published data have been found to quantify these differences, a general understanding of shoreline processes, drift-sector characteristics (Schwartz, Wallace and Jacobsen, 1989), and armoring effects can be combined to project probable drift-sector impacts (Macdonald et al., 1994).

Within the source area, the principal impact of shoreline armoring will be to impound potential sediment sources, leading to beach starvation both at the armoring site and downdrift. The hard solution will also cause significant hydraulic impacts leading to further beach narrowing, lowering, coarsening, etc. This combination—source area/hard solution—presents the worst-case scenario, in which all impacts are likely to be significant. A soft solution used in the same situation will partially offset both the impoundment and hydraulic effects, thus lowering overall impact levels. Loss of LOD may remain significant, as beach nourishment can bury or cut off existing supplies of organic debris from the feeder bluffs. The downdrift impacts of (partially) blocking off the drift sector's sediment source will be high with an armored shoreline, but could be ameliorated with a soft solution, to the extent that any artificial beach nourishment could replace impounded natural sediment sources.

Within the driftway, sediment impoundment would not be as serious a concern as in the source area, for the driftway is receiving sediments from the updrift source. Hard solutions would still cause medium to high hydraulic impacts onsite however, while soft solutions would again ameliorate local and downdrift impacts by feeding new sediment into the system.

Use of either hard or soft shore protection solutions should not be needed within the drift-sector accretion terminal or sink, as erosion should not be a concern. Should shoreline armoring be installed, however, hydraulic impacts can still be expected to occur. Since sediment is being received from updrift sources, all impacts would be relatively low-level. As noted by Schwartz and Wallace (1986), referring to Puget Sound drift sectors, "the potential for damage at any given proposed site must be evaluated and dealt with on an individual basis."

PUGET SOUND CASE STUDY RESULTS

The search for documented case examples of shore protection impacts on beaches in Puget Sound identified only a handful of sites for which some historical background and quantitative data are available. The best documented of these include Ediz Hook, Port Angeles; Lincoln Park Beach, Seattle; Sunnyside Beach, Steilacoom; and West Point South Beach, Discovery Park, Seattle. Case study highlights are

presented in the paragraphs below; evidence supporting specific beach impacts is noted in Figure 3. The reader is referred to the original study report (Macdonald et al., 1994) for full details of each case study.

Impacts / Case Studies	Ediz Hook	Sunnyside Beach	Lincoln Park	West Point	Whidbey/W. Shore	Rich Passage
Sediment Impoundment (Downdrift Impacts)	✓	✓	✓	✓	✓	✓
Beach Narrowing	✓	✓	✓	✓		
Beach Lowering	✓	✓	✓		✓	✓
Substrate Coarsening	?	✓	✓			
Loss Large Organic Debris	?	?	✓			

Figure 3. Puget Sound case studies. Documentation with strong (✓) and weaker (?) field data.

Ediz Hook (Galster and Schwartz, 1990) provides the best regional example of direct and cumulative physical impacts, from both shoreline armoring and beach nourishment on the adjacent beach. Quantitative data relating bulkheading to reduced sediment supply, narrowing and steepening of the beach profile, and slowing of spit extension are all available for known time frames. Data from tracer cobbles also provide field measurements of longshore drift rates.

Lincoln Park Beach studies (Chu, 1985; USACOE, 1986, 1992) provide quantitative data on the physical impacts of both historic seawall armoring and more recent (1988) beach nourishment. There is good evidence, including some quantitative measurements, of both beach narrowing and lowering in front of the historic seawall. Minor adjustments to beach profiles following placement of nourishment materials suggest that new equilibrium profiles have been established, and prior impacts from the seawall have been "removed." There is some evidence that winnowing of the beach nourishment material has created a natural armor layer of coarser sediment on the new beach surface, and organic debris is now accumulating.

Sunnyside Beach site history—together with a lack of natural sediment sources to the site—permits quantitative calculations of sediment movement and losses over known time periods (USACOE, 1981). Sunnyside is a "starved" system, where the beach is undergoing steady, broad retreat. The presence of a timber bulkhead in the center of an otherwise uniform beach is ideal for comparing physical changes in front of the bulkhead with those beyond the ends of the bulkhead. Increased beach erosion—including lowering and narrowing in front of the bulkhead—during the 1990-91 winter storm season was dramatic. This site provides some evidence for both the coarsening of sediments in front of a bulkhead and the loss of LOD.

West Point South Beach studies (Domenowske, 1987) document shoreline impacts following installation (1961) and removal (1980) of a riprap-walled sludge lagoon that interrupted littoral drift along a previously stable shoreline. A "soft armoring" gravel beach installed after lagoon removal (Bauer, 1979) continues to be monitored. Ongoing monitoring at Lincoln Park Beach (USACOE, Seattle District) and on Whidbey Island's west shore (Terich and Schwartz, 1993, Western Washington University) will also yield

valuable additional data. An obvious outgrowth of the scarce case study data for Puget Sound is the clear and critical need for more comprehensive field monitoring and quantitative research regarding the potential impacts of shoreline modifications.

CONCLUSIONS

Traditional studies of waves and beaches have focused on shore zone erosion, on sediment transport, and on engineering concerns about the success or failure of coastal structures. Studies of shore protection impacts on physical and biological beach processes are much more limited. A recent comprehensive annotated bibliography of shore protection physical impact studies (Kraus, 1988) cited only about 40 studies worldwide.

There is broad-based agreement that the physical impacts of hard armoring include sediment impoundment (with potential for significant downdrift impacts), beach narrowing, and shore profile lowering. All three impacts have been described from numerous widely distributed field sites as well as from theoretical and modeling studies. Very few of these studies have been conducted in Puget Sound, however. Other physical impacts discussed here—sediment coarsening, groundwater impacts, and loss of large organic debris—have not been studied systematically and generally receive only limited attention. In fact, these impacts may have very significant physical and ecological implications, especially for Puget Sound.

A broad array of general information (but very few specific studies) supports the view that identical shoreline armoring will cause very different impacts depending on where it is placed. This is true for its position in the landscape and for its position on the beach; it also appears likely that the specific nature of the armoring can significantly alter its impact. These concepts are summarized in flow diagram form in Figure 4. To echo Tait and Griggs (1991), a wide variety of interdependent factors can influence the specific impacts of shore protection on the beach at a particular site; thus beach response must be regarded as a site-specific impact.

Data concerning cumulative impact of shore protection remain extremely scarce. Results from Ediz Hook (Galster and Schwartz, 1990), Oregon's Siletz littoral cell (Good, 1992), and Gold Coast, Australia (Mcdonald and Patterson, 1985), all confirm that increased bulkheading results in cumulative impoundment of sediment sources that eventually leads to beach "starvation" and severe beach loss. By analogy, significant cumulative impacts can be expected as Puget Sound drift sector source areas are increasingly cut off (impounded) by cumulative bulkheading.

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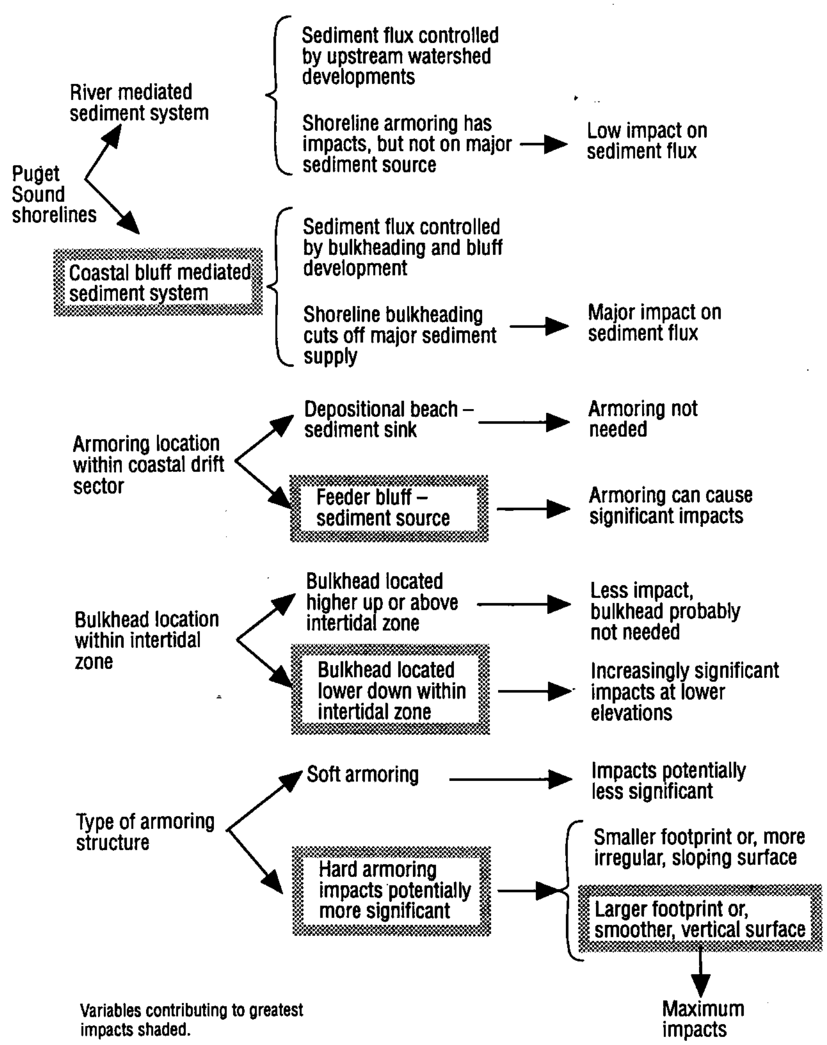

Figure 4. Impacts vary with landscape position and armoring type

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SHORELINE ARMORING EFFECTS ON BIOLOGICAL RESOURCES AND COASTAL ECOLOGY IN PUGET SOUND

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INTRODUCTION

Development along coastal areas of the United States has been extensive. Culliton et al. (1992) estimated that between 1970 and 1989 about half of all residential and non-residential construction in the United States occurred in the federally designated coastal zone. During this period, approximately 640,000 permits for construction in coastal counties of Washington state were issued. Many coastal structures in Washington are built dangerously close to the shoreline, where natural erosion can threaten property (Canning and Shipman, 1993). To protect these properties, erosion control structures such as concrete or rock bulkheads are often erected. However, these and other types of shoreline armoring can have adverse effects on biological resources and coastal ecology (Thom et al., 1994a). In the worst case, shoreline armoring can totally alter the physical structure of the beach and adjacent upland habitats (Downing, 1983). Alteration of the physical conditions of the shoreline can cause changes in the biological structure and functioning of shoreline habitats and can also alter use of these habitats by fish, shellfish, birds, and other organisms.

This paper provides an overview of the effects of shoreline armoring on habitat structure, ecological processes, and selected biological resources of the nearshore zone of Puget Sound. In addition, we briefly address cumulative ecological effects—potentially the most damaging but least understood effects of shoreline armoring.

ARMORING EFFECTS ON HABITAT STRUCTURE

Habitat structure is defined here as substrata type or types along with the associated communities of organisms. Shoreline armoring affects habitat structure directly and indirectly by altering physical conditions. Habitats do not cease to exist, but shift from one type to another. In fact, the armoring material itself becomes a habitat type. The factors that must be considered in order to predict the habitat shift include: (1) the initial condition of substrata and exposure to waves and current, (2) the degree of alteration of sediment supply to the system, (3) the geological characteristics of the subsurface materials, (4) the time frame for the shift, and (5) the predicted habitat that will form under new physical conditions. A limited data set on geological conditions of subsurface materials on beaches of Puget Sound comes from core samples collected for stratigraphy analysis by Beale (1990), Atwater and Moore (1992), and Bucknam et al. (1992). These data are incomplete for all Puget Sound nearshore habitats but do provide an indication of types of materials that would be exposed by erosion at selected sites. The most prevalent substratum on Puget Sound shorelines is coarse sand and gravel (Downing, 1983). This substratum equates with Dethier's (1990) habitat types of "mixed coarse-open" and "gravel-open" habitats. These habitats deserve special attention because they are the most likely to be subjected to increased erosion as a result of shoreline armoring.

Lincoln Park Seawall Case History

The events following seawall construction on the southwest side of Point Williams at Lincoln Park beach in West Seattle provide an excellent indication of some changes that can be expected in habitat structure following shoreline armoring. The vertical seawall was placed at the upper elevations of the beach in the mid-1930s. By the 1950s, the beach had eroded dramatically and changed from what was

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probably a coarse sand substrate mixed with gravel and cobble to a substrate consisting of hard-packed clay with scattered cobbles. The lower portion of the beach was probably eroded also, as was the subtidal zone immediately seaward of the beach. The substrate changed from mixed-coarse sand through hardpan, and the elevation of the beach dropped on the order of several feet in some areas (Macdonald et al., 1993).

The change in elevation and substrata affected the types of plants and animals that lived on the beach (Figure 1).

The extensive data on Lincoln Park macroalgal communities (Rigg, 1917; Thom and Hallum, 1990), intertidal communities (Armstrong et al., 1976; Thom et al., 1976), and the effects of nourishment of the beach with pit-run gravel (Thom and Hampel, 1985; Thom, 1988; Thom and Hallum, 1989; Hiss et al., 1990; Thom and Hamilton, 1991; Antrim et al., 1993; PENTEC, 1993) verify that, within two decades, the habitat structure changed from a relatively sparse community of interstitial detritivores to a community dominated by sessile macrofauna and seaweeds. The kelp bed increased in size from a maximum length of 215 m between 1914 and 1917 (Rigg, 1917) to a minimum length of 600 m since 1974 (Thom and Hallum, 1990). The evolution of the beach probably proceeded from a mixed-coarse sand habitat, through gravel, to hardpan. At the same time, the elevation lowered and the profile of the beach flattened substantially. Lincoln Park provides the best example of what is likely to happen to the most common Puget Sound shoreline habitat type (mixed coarse sand and gravel) as a result of severe armoring effects.

Species Assemblage Shifts

Dethier's (1990) habitat classification scheme can be used to predict species assemblage shifts that may result from shoreline armoring. Marsh erosion in partly enclosed conditions would predictably proceed from an assemblage dominated by marsh plants, to a sand assemblage dominated by infaunal bivalves, worms, and amphipods, to an assemblage dominated by organisms preferring gravel substrates. The rate of change in species assemblages is unknown but is probably slower in protected habitats than under more open conditions.

Open sand would erode to mixed-coarse sand, gravel, hardpan, and, finally, bedrock. This change in substrate type would mean a shift from an assemblage dominated by small crustacea (harpacticoid copepods, amphipods) at higher elevations and eelgrass (*Zostera marina*) in the lower intertidal zone; through an *Ulva* spp.-hardshell bivalve assemblage; to an assemblage containing primarily crustaceans such as isopods and large amphipods; to an assemblage of barnacles and rock-boring bivalves; and finally to an assemblage of barnacles and seaweed. Existing open gravel habitats would essentially erode to hardpan and then bedrock. The rate of change from beach sand to hardpan, based upon Lincoln Park data, would be on the order of 20 years. Periodic storm events would speed the rate of habitat alteration along some portions of the beach.

Hard substrata such as a concrete vertical seawall, riprap breakwaters, and gabion walls can be colonized by a hard bottom assemblage. This assemblage, in the higher intertidal zone, consists of barnacles, mussels, and macroalgae such as rockweed (*Fucus* spp.) and sea lettuce (*Ulva* spp.). Under stable conditions, rockweed can become quite dense on riprap breakwaters and shoreline protection structures, as has been shown for West Point (Thom, 1993) and the Fraser River estuary (Pomeroy and Levings, 1980).

ARMORING EFFECTS ON ECOLOGICAL PROCESSES

Altered plant community composition and primary productivity, net loss of organic matter, and altered nutrient cycling are the principal effects of armoring on ecological processes.

Plant Community Composition and Primary Productivity

Plants vary in the rates at which they fix carbon (primary productivity). Hence, alterations in habitat structure that result in changes in the types and abundances of plants (i.e., plant community composition) on the shore could also result in altered primary productivity rates for that shore. Figure 2 shows annual

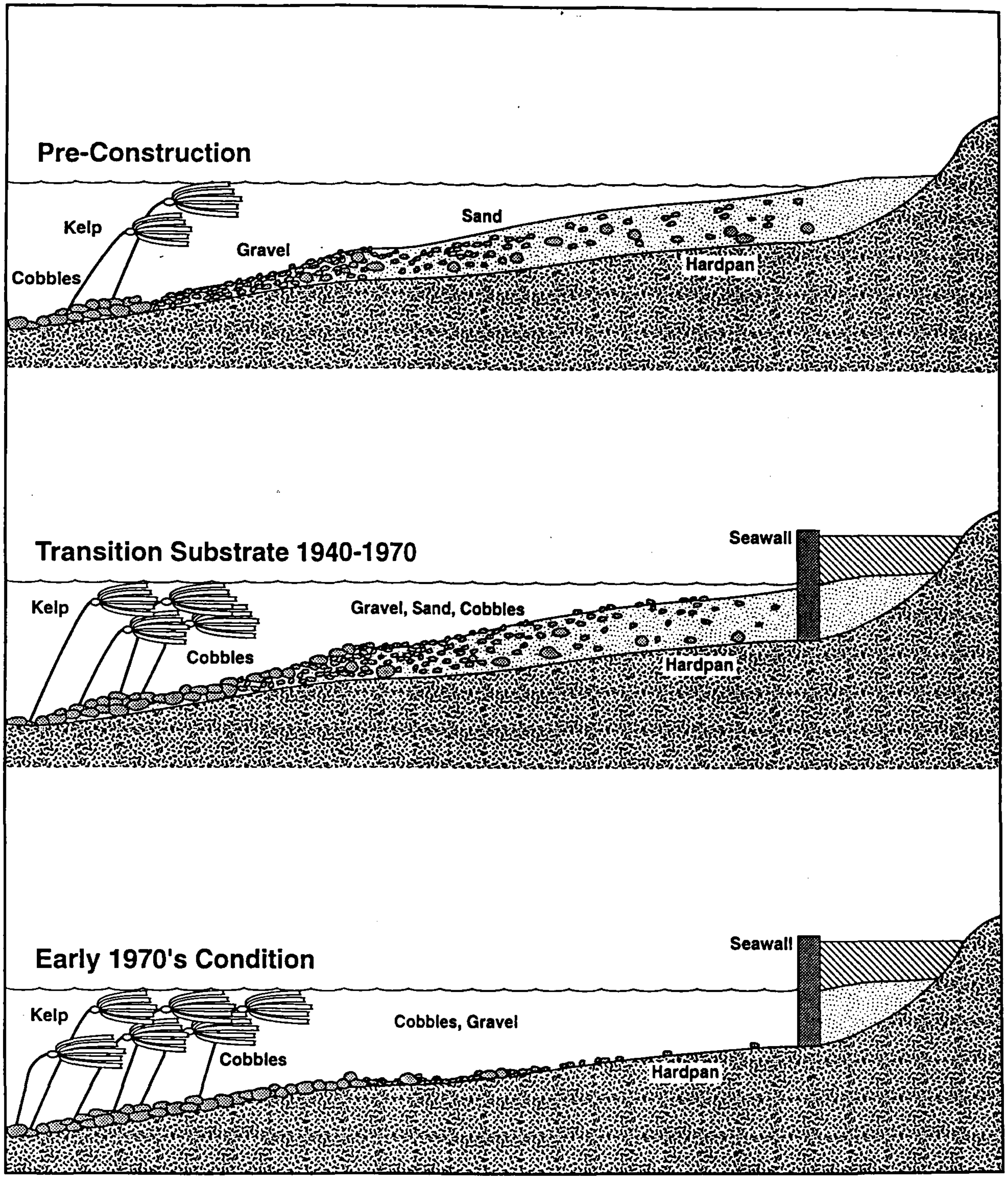

Figure 1. Progression of habitats at Lincoln Park Beach, Seattle, 1917-1970

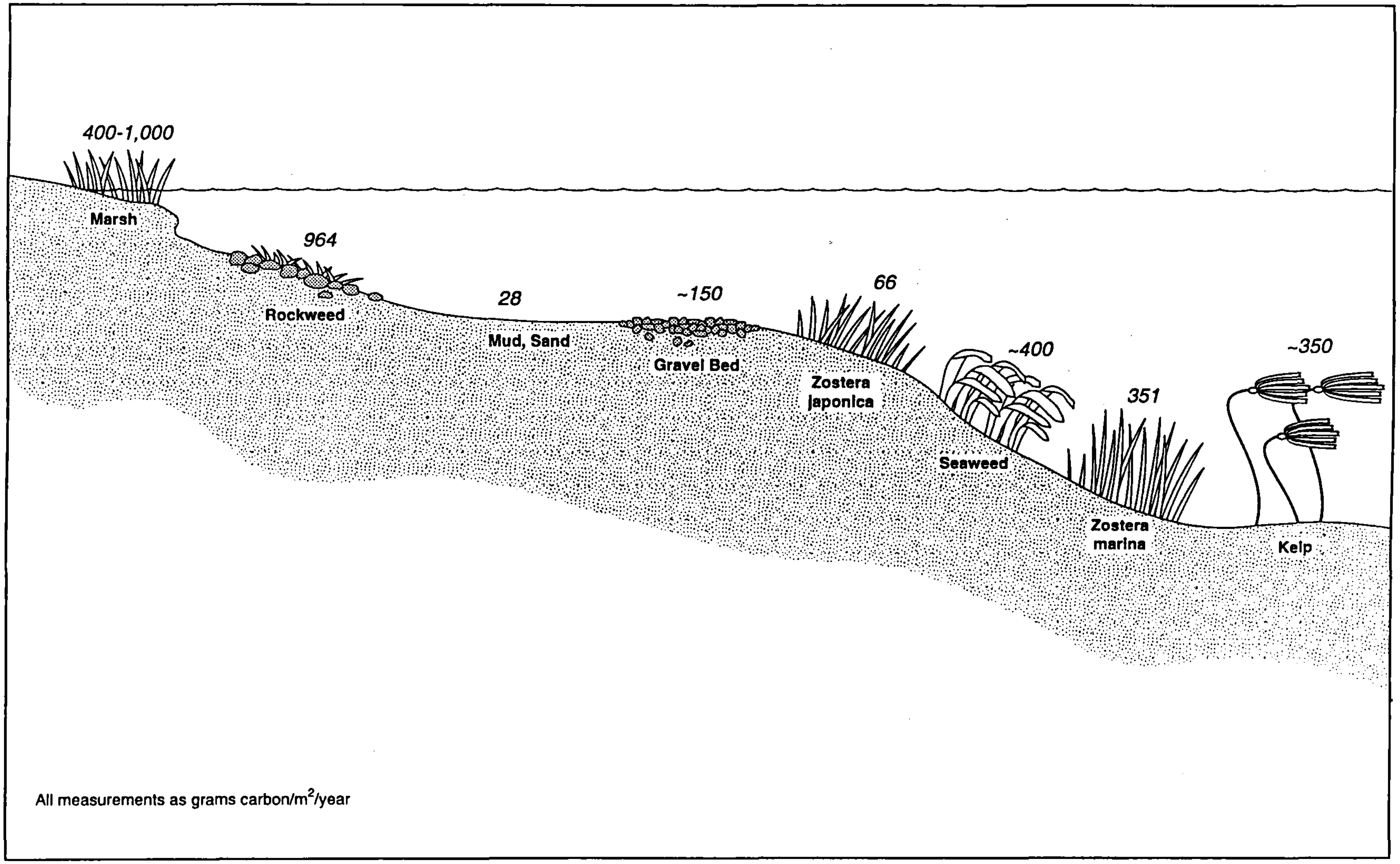

Figure 2. Puget Sound annual net primary productivity rates by habitat (Source: Thom and Albright, 1990)

primary production rates for different intertidal and subtidal habitat types in Puget Sound. In general, the rates range between 200 and 500 g C m^{-2} y^{-1}.

These data can be used to predict shifts in productivity resulting from changes in substrata type. For example, placement of rock on the upper intertidal zone will result in a loss of production by microalgae and an increase in productivity by rockweed and sea lettuce. Pomeroy and Levings (1980) found that, although placement of a rock jetty on the Fraser River delta resulted in increased surface area for algal growth, there was no appreciable enhancement of primary productivity as compared to the natural marsh/mudflat system. Data from investigations of the effects of placement of gravel on mud/sand beaches for enhancement of clam production showed that net primary productivity in graveled areas did not significantly differ from natural areas, despite dramatic changes in plant community composition (Thom et al., 1994b). At one of the graveled sites (Semiahmoo Bay), the community changed from a dense eelgrass meadow to a gravel patch dominated by green algae, mussels, and barnacles. These studies indicate that altered beach substrata—as might be expected to result from shoreline armoring—can change the plant community composition, but may not alter the productivity rates per unit area.

Organic Matter Flow

Shoreline armoring has been shown to increase erosion rates on beaches. Increased erosion can convert the beach from a system that shows net accumulation of organic matter to one that shows net loss of organic matter on an annual or seasonal basis. Organic matter accumulates on the beach from adjacent updrift beaches and uplands; this organic matter can either be deposited on the beach and cycled there or be exported to adjacent areas. Alterations in the dynamics of organic matter production and deposition can dramatically change the beach communities.

Organic matter in the form of seaweed, seagrass, marsh plants, and terrestrial plant leaves accumulates on beaches in Puget Sound. A peak in drift material generally occurs in summer, with little material remaining during winter. Under extreme conditions, piles of seaweed can be 0.5 m thick and cause anoxic conditions immediately under the mat (Thom et al., 1988). A comparison of drift material dynamics was made at Seahurst Park in West Seattle by Thom and Albright (1990). They found that a site located next to a natural bluff shoreline (high site) had drift accumulations primarily of seaweeds, but also containing large quantities of tree leaves. Seaward of a gabion wall that armored another portion of the beach, however, drift material was located lower on the beach and contained very little leaf material. The size of the drift material patches were on the order of 300 m^2 during peak periods (Thom et al., 1984). Although not quantified, drift material high on the beach was noted to contain insects as well as amphipods, which were probably actively using the organic matter. Amphipods were also abundant in the seaweed drift lower on the beach. The gabion wall caused erosion along the seaward portion of the beach. The erosion has affected the source of organic matter to the beach, by removing trees and shrubs, and has also changed the location and composition of detritus accumulating on the beach.

Nutrient Dynamics

Placement of shoreline erosion control structures alters substrate and habitat characteristics of a beach, which in turn alters the nutrient dynamics of the system. Streams and rivers are an important supply of nutrients to Puget Sound ecosystems (Thom and Albright, 1990). Interruption of stream flows will remove potential sources of fresh water, in addition to inorganic nitrogen compounds, phosphate, and other materials. A small urban stream flowing onto Lincoln Park beach contained very high concentrations of nitrate, which were well above ambient Puget Sound levels (Thom et al., 1988). This loading is believed to have caused massive blooms of *Ulva* spp. on the beach, which accumulated in high enough quantities during the summer to cause odor problems. The problem was so severe in the 1980s that residents were complaining of illnesses related to the smell on the beach. The seaweed formed piles in a relatively small area of the beach following summer windy periods (usually in July), but by the end of the summer the material was removed by natural currents, and the odor ceased to be a problem. Whether the buildup of the seaweed was directly due to shoreline armoring is in question, but this portion of the beach is backed

by a seawall, and residents claim that the morphology of the beach has changed dramatically over two to three decades.

Studies by Thom et al. (1994b) on the effects of beach graveling on clam production also examined the effects on nutrient fluxes from the beach. They found that graveling significantly increased the flux of ammonia, a breakdown product of organic matter, from the benthos to the water column. Organic matter was apparently more easily trapped by the gravel, resulting in higher densities of detritivores and bacteria. This, in turn, resulted in enhanced remineralization rates and fluxes and increased benthic respiration rates in the graveled areas. Hence, changing a sand/mudflat to a gravel habitat can be expected to significantly alter nutrient cycling on beaches.

Macdonald et al. (1993) noted that a concrete seawall will increase groundwater pore pressures by allowing hydraulic pressure to build up landward of the wall. Increased pore pressure can result in increased hydraulic pressure that exacerbates erosion seaward of the wall. In addition, the flow of nutrients in the groundwater to the beach could also be altered (Sapik et al., 1988).

ARMORING EFFECTS ON BIOLOGICAL RESOURCES

The documented and predicted effects of shoreline armoring on selected finfish, hardshell clams, and other invertebrates of commercial or recreational importance are summarized in Figure 3.

The species listed in this figure were identified by Niel Rickard of the Washington Department of Fish and Wildlife (WDFW) (personal communication) as the species most likely to be negatively affected by shoreline armoring. WDFW concerns center around the critical importance of beaches for finfish spawning, foraging, and rearing, and as habitat for adult and juvenile invertebrates. Potential armoring effects on these species include: (1) habitat shifts (e.g., coarsening of substrate, changes in benthic vegetation, changes in primary production and nutrient flow, net loss of organic matter, and shading), (2) loss of spawning habitat, (3) loss of shoreline riparian vegetation, (4) loss of wetland vegetation, (5) loss of large organic debris, (6) changes in food resources, and (7) loss of migratory corridors.

In general, the direct effects of shoreline armoring on fish and invertebrate communities have not been well documented. Because shoreline armoring has no analogue in the natural disturbance regime, direct effects on fish or invertebrates are difficult to quantify or observe, let alone predict.

Perhaps the best available information on shoreline armoring effects is WDFW field observations. WDFW has observed four primary effects of shoreline armoring on surf smelt, sand lance, and rock sole: (1) reduced sediment input from feeder bluffs, (2) permanent loss of habitat $^{+}$5 ft MLLW and above, 3) loss of shoreline riparian vegetation that provides shade to the upper beach, and 4) changes in substrate from finer- to coarser-grained material (Dan Penttila, WDFW, personal communication, December 1993). In an effort to protect these species and their spawning habitats, WDFW issued a new draft section to the Hydraulic Code (Chapter 220-110-285 WAC) in 1993, which specifies that "Single-family residence bulkheads shall not result in permanent loss of critical food fish or shellfish habitat."

CUMULATIVE ECOLOGICAL EFFECTS

The cumulative ecological effects of shoreline armoring are probably of greatest concern to resource managers. Yet, the cumulative effects of incremental shoreline armoring in Puget Sound are largely unknown. Cumulative effects can be defined as the sum of all individual effects to an ecosystem. While individual, small armoring projects may have little measurable ecological effect, incremental increases in the number of small projects within an embayment would be expected to result in significant effects to the bay ecosystem. The point at which these cumulative effects result in significant reduction in the ecological functions of the bay can be referred to as the threshold or catastrophe point (Forman and Godron, 1986).

Thurston County shoreline is among the most extensively armored counties bordering Puget Sound. As of 1993, approximately 30 percent of the 117 miles of shoreline in the county was armored (Morrison et al., 1993). This county contains primarily depositional beaches (Downing, 1983), and modification in the beach elevations as well as coarsening of substrata would be predicted because of the armoring.

RESOURCE SPECIES	Armoring-related Habitat Shift [1]	Loss of Spawning Habitat	Loss of Shoreline Riparian Vegetation	Loss of Wetland Vegetation	Loss of Large Organic Debris	Changes in Food Resources	Loss of Migratory Corridors
Surf Smelt	●	●	●		◍		
Pacific Sand Lance	●	●	●		◍		
Rock Sole	●	●	●		◍		
Juvenile Salmonids [2]	●		●	●	●	●	●
Pacific Herring	◍	◍					
Hardshell Clams [2]	●	◍[3]				●	
Geoduck	○						
Oysters	○	○				○	
Dungeness Crab	◍	◍[3]				◍	
Sea Cucumber	○					○	
Sea Urchins	○					○	

ARMORING EFFECTS

Key

● Well documented evidence of negative effects.

◍ High potential for negative effects but not documented.

○ Some potential for longterm effects but not documented.

Footnotes

[1] Includes coarsening of substrate, changes in benthic vegetation, changes in primary production and nutrient flow, potential net loss of organic matter and shading.

[2] Multiple species.

[3] Loss of habitat for settlement.

Figure 3. Summary of armoring effects on selected biological resources of Puget Sound

As was discussed above for Lincoln Park, coarsening of subtidal sediment may have resulted in a substantial increase in kelp. The shoreline of this beach, which includes a steep bluff over about 40 percent of the shoreline, is virtually 100 percent armored with a vertical seawall. The change at Lincoln Park from a gravel habitat to a hardpan habitat with subsequent increases in the kelp distribution could be viewed as an alteration that exceeded the threshold point for that bay. Based on comparisons of surveys made in 1911-12 and 1977, southern Puget Sound showed the second largest increase in kelp distribution (+332 percent) among all regions of Puget Sound (Thom and Hallum, 1990). It was second only to the main basin (the area between Tacoma and the southern tip of Whidbey Island), which had an increase of 483 percent in shoreline bordered by kelp. The linkage between armoring, sediment composition, and kelp distribution requires further study but may prove to be an indicator of cumulative effects of shoreline armoring in the region. The cumulative effect of shoreline armoring on finfish and shellfish in Thurston County is unknown. We would predict a decrease in plants and animals dependent upon intertidal soft substrata and an increase in plants and animals associated with gravel and cobble bottom.

Available data indicate that increases in disturbance from contamination and physical modifications of the shoreline have resulted in measurable changes in habitats in Puget Sound (Thom and Hallum, 1990). However, we currently lack an understanding of the linkages between the degree of disturbance caused by shoreline armoring and resulting changes in habitat distribution and function. Furthermore, data are lacking to quantitatively link changes in nearshore habitats (that might be affected by armoring) with resultant changes in the numbers and types of fishery resources. Nevertheless, two recent frameworks developed for cumulative impact assessment of wetlands (Gosselink et al., 1990; Leibowitz et al., 1992) could be used to begin making these linkages.

CONCLUSIONS AND RESEARCH NEEDS

This report provides a brief overview of the documented and predicted effects of shoreline armoring on habitat structure, ecological processes, and selected biological resources of the nearshore zone of Puget Sound. While there is ample evidence illustrating the effects of shoreline armoring on the physical structure of Puget Sound's beaches (Cox et al., 1993; Macdonald et al. 1993; Morrison et al., 1993), the ecological effects associated with these physical changes are poorly understood in Puget Sound and are not well documented anywhere in the United States (Thom et al., 1994a).

Changes in physical structure that can result from shoreline armoring include loss of shade, reduction in litterfall, lowering of beach profiles, coarsening of beach sediment, shortening of the beach, and alteration of groundwater flows. Based upon the critical links between physical conditions and habitats and links between habitats and biological resources, some conclusions can be made about potential effects of armoring on the ecology of beaches; the following conclusions are verified by anecdotal observations and data from a small number of beaches: (1) habitat structure is modified under severe armoring conditions such that fine-sediment beaches are eroded down to gravel cobble or hardpan within a few decades; (2) armoring may have its most pronounced ecological effect along gravel-cobble beaches as opposed to highly depositional (mudflat) beaches or protected marshes; (3) along gravel-cobble beaches, the classic physical changes alter the substrata from one that favors the growth of hardshell clams to one that is dominated by surface-dwelling seaweed, kelp and barnacles; (4) shallow subtidal areas adjacent to armored beaches can show significant alterations in substrata and biological communities under severe conditions; (5) processes such as organic matter deposition and nutrient flux rates are altered as the physical conditions and substrata change; (6) surf smelt, sand lance, herring and rock sole spawning areas could be lost due to removal of fine sediments and woody debris from the intertidal zone; (7) hard structures provide poorer habitats for prey resources for many benthic-feeding fish including juvenile salmon; (8) cumulative effects of physical changes can result in major alterations in the habitats found in a system; (9) it is not possible to quantitatively predict the effects of armoring on the ecology of beaches and biological resources they support, although simple calculations based upon very limited data indicate an approximate 1 to 1 alteration of habitat distribution associated with length of shoreline armored; and (10) most information on impacts was gathered from beaches that can be characterized as being significantly changed by armoring; there are,

however, examples in Puget Sound where armoring was done in such a manner as to have little impact on the beach ecology.

There are several fundamental data gaps that require research to better understand and predict the effects of shoreline armoring on the ecology of Puget Sound beaches. An abbreviated list of research needs includes: (1) an inventory of the historic and current areas of specific habitats available for critical biological resources (e.g., surf smelt spawning habitat, intertidal wetland vegetation) and quantification of the areas of these habitats adversely affected by various armoring techniques; (2) systematic, long-term studies of existing armored sites; (3) experimental studies to evaluate new or unique technologies (e.g., headland and pocket beach systems, shoreline vegetation enhancement); and (4) cumulative effects model development.

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1993). Fortunately Shorelands was successful in obtaining funding under the federal Coastal Zone Management Act section 309 improvement grants program to carry out the CEMS project.

The CEMS project sought to resolve three issues: (1) identification of the geological engineering and bioengineering erosion protection techniques appropriate to Puget Sound; (2) analysis of the nature and relative severity of the cumulative effects of shoreline armoring techniques upon physical and ecological resources and processes; and (3) development of model regulatory approaches for erosion hazard management for both existing and new construction through the following tasks.

Task 1: Determine the extent, rate, and character of recent shoreline armoring. No quantitative data existed, only professional observations and opinions. Remedying this deficiency has permitted a quantitative discussion on the extent and nature of shoreline armoring over the past 15 years, and how that shoreline hardening has correlated with land-use types and densities. Thurston County was selected as the study area because of the availability of large amounts of relevant data already in data management and GIS computer file formats.

Task 2: Establish the appropriate engineering and geotechnical standards for shoreline erosion management under different energy regimes. This task assessed the engineering and geotechnical appropriateness of selected alternatives (bulkheading, revetments, beach nourishment, no action, etc.) in relation to characteristic wave energy and geologic conditions. The geotechnical and engineering standards analyzed under Task 2 include the common coastal erosion management methods. Starred (*) items are ones in common use on Puget Sound shorelines and were emphasized.

Hard Structures: bulkheads; *seawalls; *revetments; breakwaters; prefab/patent systems; gabions; grout bags; floating attenuators.

Soft Structures: *sand and/or gravel nourishment; beach strands; vegetation; slope drainage control; beachface dewatering; slope regrading. (Soft structures imply compliant structures, not necessarily natural or non-impacting structures or systems.)

Composite Systems: headland/pocket beach; perched beach; groin field. (Composite systems imply a mix of hard and soft features.)

Nonstructural Methods (e.g., reducing overburden pressure): building setbacks; drain field relocation/removal.

Task 3: Evaluate the cumulative effects of shoreline armoring on physical coastal processes in Puget Sound. The key assumptions and questions about the effects of shoreline armoring on coastal processes are evaluated based on the technical literature and sensitized to Puget Sound conditions. Selected local case examples are provided.

Task 4: Evaluate the existing regulatory approaches for coastal erosion management in common use and assess their relative strengths and weaknesses. Regulatory and non-regulatory approaches to coastal erosion management were evaluated, and policy alternatives for Washington were assessed. Permits for shoreline armoring are obtained at the local government level through the Shoreline Substantial Development Permit process contained in the local Shoreline Master Program. Most are processed as exemptions to the SDP. The state SMA provides a framework within which local governments adopt local Shoreline Master Programs consistent with state goals but attuned to local conditions. (Permit applicants must also comply with the requirements of the Department of Fish and Wildlife Hydraulic Project Approval code and the U.S. Army Corps of Engineers' Department of the Army Permit [Clean Water Act Section 404]). This report will provide the basis (in part) for development of state guidance to local government for adoption of erosion management procedures.

Task 5: Evaluate the secondary effects of shoreline armoring physical effects on ecological systems in Puget Sound. Following on from Task 3, the direct effects of shoreline armoring are assessed as well as the secondary effects of changes to coastal processes and conditions upon biological resources are assessed. Habitats and biological resources emphasized were based on recommendations of the Washington Department of Fish and Wildlife. Selected local case examples are provided.

Task 6: Evaluate the management options for unstable coastal bluffs in Puget Sound. This comprehensive assessment of engineering, geotechnical, bioengineering, and vegetation management techniques for

slope stabilization will provide the basis (in part) for development of guidance to local government and land owners. A large measure of bulkheading is in reaction to slope failures, not shoreline erosion *per se*. Slope instability is caused by a combination of inherent geologic weaknesses, groundwater loading, and toe erosion. A combination of construction setbacks, groundwater management, and shoreline erosion management will be needed for a balanced approach.

Task 7: Evaluate the viable regional approaches to coastal erosion management. Many "soft" approaches to erosion management (e.g., beach nourishment) or mitigation for adverse effects must be carried out on a regional basis to be effective. Both the technical and political feasibility of regional erosion management is assessed.

Task 8: Study program integration. Shorelands staff is developing a programmatic environmental impact assessment.

Task 9: Develop Shoreline Master Program model elements. Based on the foregoing findings, this task will formulate specific model elements that can be recommended as amendments to local Shoreline Master Program regulations. The guidance will be published as a chapter in Ecology's *Shoreline Management Guidebook.*

Tasks 1, 3, and 5 are reported on in other papers at this symposium (Kettman, 1995; MacDonald, 1995; Thom, Shreffler and MacDonald, 1995). This paper emphasizes overall conclusions and policy implications. Shorelands will issue its policy and regulatory recommendations to local government in 1995-96.

RESULTS AND CONCLUSIONS

In general, we conclude that widespread shoreline armoring affects Puget Sound by:

- cutting off sources of sediment supply to nearby beaches, thus leading to "starvation" of the beaches for the sand and other fine-grained materials that typically make up a beach (most beach sand and gravel in Puget Sound is derived from bank and bluff erosion);
- transforming, in time, a sandy beach into gravel or cobbles, or even scouring down to bedrock or, more common in the Puget Sound region, a hard clay;
- lowering the beach profile, exposing the footings of armoring, leading to reentries onto the beach for repairs;
- secondarily eliminating vegetation that shades the upper beach, thus degrading the value of the intertidal area for spawning habitat; and
- affecting the kind of life the beach can support through transformation of the character of the beach.

The most egregious examples of shoreline armoring combined with beach fill occurred before the Shoreline Management Act and Hydraulics Code were enacted. Many acres of intertidal habitat on Hood Canal and elsewhere in Puget Sound were permanently lost.

Few distinctions in the degree of impact of shoreline armoring techniques were identified; more important was the location of the armoring relative to ordinary high water and the toe of the bank or bluff.

POLICY IMPLICATIONS

Bulkheading is defined as a "development" subject to the SMA (90.58.030 (3)(d)). However, "construction of the normal protective bulkhead common to single family residences" is not considered to be substantial development [90.58.030 (3)(e)] subject to the requirement for a substantial development permit. Construction of the "normal protective bulkhead common to single family residences" is still subject to the provisions of the SMA and the local SMP.

The "normal protective bulkhead common to single family residences" is "constructed at or near the ordinary high-water mark to protect a single family residence and is for protecting land from erosion, not for the purpose of creating land. Where an existing bulkhead is being replaced, it shall be constructed no

further waterward of the existing bulkhead than is necessary for construction of new footings" [WAC 173-14-040 (c)].

The distinction between a "normal protective bulkhead common to single family residences" and one that allows land creation or beach fill is not defined in the SMA regulations. (The U.S. Army Corps of Engineers in effect makes this distinction by defining the threshold for consistency with their "nationwide permit" for shoreline armoring exemption from full permit review under the Clean Water Act to be where backfill is less than one cubic yard per lineal foot of armoring.)

ESB 6128 required that "each master program shall contain standards governing the protection of single family residences and appurtenant structures against damage or loss due to shoreline erosion. The standards shall govern the issuance of substantial development permits for shoreline protection, including structural methods such as construction of bulkheads, and nonstructural methods of protection" [90.58.030 (6)].

Implementation of the provisions of ESB 6128 must

- clarify the distinction between a "normal protective bulkhead common to single family residences" and one that permits land creation or beach fill;
- distinguish between existing residences and those first occupied after January 1, 1992;
- address mitigation where the armoring is not "designed to minimize harm to the shoreline natural environment;" and
- address expeditious permit processing.

Some of these needs are summarized in Table 1. Policy alternatives studies conducted under tasks 4 and 7 assessed alternatives for both individual parcel (McCabe and Wellman, 1994a) and regional approaches (McCabe and Wellman, 1994b) to erosion management.

Table 1. Matrix of pre- and post-adoption criteria

<table>
<tr><th rowspan="3">Beach and Bluff Characteristics</th><th colspan="2">Pre-Adoption Criteria</th><th colspan="3">Post-Adoption Criteria</th></tr>
<tr><th colspan="2">Existing House</th><th rowspan="2">New Platting</th><th colspan="2">New House Building Permit on Existing Parcel</th></tr>
<tr><th>Application for New Measure</th><th>Application for Repair or Replacement</th><th>Small Parcel</th><th>Large Parcel</th></tr>
<tr><td>Accretion Beach</td><td colspan="5">No erosion protection measures permitted as no erosion is occurring? Landscape walls above OHW permitted? What about fill above OHW to bring building site above flood zone?</td></tr>
<tr><td>Eroding Beach</td><td>Necessary 'normal' armoring permitted.</td><td>Repairs and replacement on same footprint permitted.</td><td rowspan="2">No armoring permitted? Dedication of critical area zone required as a condition of plat approval?</td><td>Necessary 'normal' armoring permitted.</td><td rowspan="2">No armoring permitted? Mandatory setback of all structures including appurtenant structures; no exceptions for geotechnical report?</td></tr>
<tr><td>Feeder Bluff</td><td>Necessary 'normal' armoring permitted. Mitigation required.</td><td>Repairs and replacement on same footprint permitted. Mitigation required.</td><td>Necessary armoring permitted. Mitigation required.</td></tr>
<tr><td>Vegetated Bluff</td><td colspan="5">Dedication of vegetation management overlay zone required as a condition of approval of any application? Vegetation management to be in accordance with criteria to be determined?</td></tr>
</table>

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PUGET SOUND RESEARCH '95

SESSION 1C

WETLANDS AND URBAN STORMWATER

Session Chair:

Richard Horner

Puget Sound Wetlands and Stormwater Management Program

OVERVIEW OF THE PUGET SOUND WETLANDS AND STORMWATER MANAGEMENT RESEARCH PROGRAM

Richard R. Horner[1]

INTRODUCTION

The Puget Sound Wetlands and Stormwater Management Research Program is a regional effort focusing on freshwater wetlands representative of those in the Puget Sound lowlands that are or may become affected by urban stormwater and associated influences of urbanization. The goal of the program is to improve the management of both urban wetland resources and stormwater on the basis of information gathered through a research process. This process uses a sound scientific design, so that the results and their application in management will be defensible.

THE ISSUES

The program originated with proposals by stormwater managers and developers in the mid-1980s to store urban stormwater runoff in wetlands in order to prevent flooding and protect stream channels from the erosive effects of high peak flow rates. There was also interest in exploiting the known ability of wetlands to capture and hold many pollutants in stormwater and thereby interrupt their transport downstream to lakes, streams, and, ultimately, Puget Sound. Resource managers countered these proposals by noting that flood storage and pollutant trapping are only two of the numerous ecological and social functions of wetlands. They further noted that using wetlands for stormwater management purposes could negatively affect these other functions, and that there was little or no basis for assessing the likelihood, extent, and consequences of such effects.

A complicating factor that came to the fore in early discussions was that wetlands in changing watersheds will be affected by that change whether or not there is planned use of them in stormwater management. In fact, redirecting runoff away from wetlands to avoid the effects of altered quantity and quality of water would deprive them of their water supply and, possibly, threaten their continued existence as wetlands.

Representatives of the stormwater and resource management communities that were debating these issues formed a committee in early 1986 to consider the best course of action to resolve them. Members came from federal, state, and local agencies; academic areas; and local interests. They were eventually drawn from seven Puget Sound counties. The King County Resource Planning Section coordinated the committee's work. The committee initially concentrated on a basic definition of the types of wetland resources about which decisions pertaining to urban stormwater management have to be made and the general types of effects that could be created in them. The committee members also oversaw a literature review, designed to determine the extent to which previous work could address the issues before them, and a management needs survey.

WETLAND RESOURCES AND THE POTENTIAL PROBLEMS OF URBANIZATION

The wetlands principally affected by the expected urbanization pattern in the Puget Sound region are freshwater systems in headwater areas or isolated from other water bodies, known as palustrine wetlands (Cowardin et al., 1979). They are located primarily in the western and west-central portions of the counties on the east side of Puget Sound, as well as around development centers on Puget Sound's islands and the counties on the west shore. These palustrine wetlands typically have some combination of water and vegetation zones consisting of open water with only submerged or floating plants or no vegetation, shallow or deep marsh containing herbaceous emergent plants, shrub-scrub vegetation, and/or a forested community.

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A special wetland type of considerable interest is a "poor fen," commonly and mistakenly called a bog, which gets water supply only from precipitation and groundwater. The lack of surface water inflow restricts nutrient availability and results in a relatively unusual plant community adapted to low nutrition and the attendant acidic conditions. Such a community is vulnerable to increased nutrient supply and buffering by surface water additions.

With urbanization, all of these wetland types are potentially subject to modifications in the quantity and quality of water that they receive and the patterns by which they receive it. Specific stormwater management actions could increase the impacts of these modifications over those that would occur with incidental drainage from an urbanized watershed. For example, raising the outlet and controlling the outflow rate would, in general, change water depths and the pattern of rise and fall of water. Structural revisions to improve pollutant trapping ability would increase toxicant accumulations, in addition to the direct effects of construction. On the other hand, stormwater management actions could be linked with efforts to upgrade wetlands that are already highly disturbed.

LITERATURE REVIEW AND MANAGEMENT NEEDS SURVEY

The principal activity of the program's first year was a comprehensive literature review, which concluded with a report (Stockdale, 1986a) and an annotated bibliography (Stockdale, 1986b) covering the reported research and observations relevant to the issues. The review was later updated (Stockdale, 1991). These reviews concentrated on what was known and what was not known about these issues at the time. Best known was the performance of wetlands in capturing pollutants, mostly derived from studies on their ability to provide advanced treatment to municipal sewage effluents. Only a small body of information pertained to stormwater. The greatest shortcoming concerned the ecological impacts to wetlands created by any kind of waste stream. The literature reviews also made clear the dearth of research on any aspect of Pacific Northwest wetlands relative to some other areas. Many detailed aspects of the subject were very poorly covered, including the relative roles of hydrologic and water quality modifications in stressing wetlands and the transport and fate of numerous toxicants in wetlands.

With the basis offered by their discussions and the literature review, the committee members participated in a formal survey designed to identify the most important needs for reaching the goal of protecting wetlands in urban and urbanizing areas, while improving the management of urban stormwater. The survey involved rating a long list of candidate management needs with respect to certain criteria. Computer processing of the ratings led to the following list of consensus high-priority management needs:

- definition of short- and long-term impacts of urban stormwater on palustrine wetlands;
- management criteria by wetland type;
- allowable runoff storage schedules that avoid or minimize negative effects on wetlands and their various functions; and
- features critical to urban runoff water quality improvement in wetlands.

RESEARCH PROGRAM DESIGN

With the availability of the literature review and management needs survey, the committee and staff assembled by King County turned to defining a program of research to serve these identified needs. The program that eventually took shape incorporated the following major components:

- wetland survey;
- stormwater impact studies;
- water quality improvement study; and
- laboratory and special field studies.

The wetland survey's purpose was to provide a broad picture of freshwater wetlands representative of the Puget Sound lowlands, specifically how urban wetlands differ from wetlands lightly affected by human activity. Covering 73 wetlands throughout lowland areas of King County, the survey's design, results, and conclusions were reported by Horner et al. (1988) and Horner (1989). Its findings assisted in designing the remainder of the research program.

Intended to fill the highest-ranking management needs, the stormwater impact studies form the core of the program. This field research is supplemented by the laboratory and special field studies, which allow investigation of certain questions under more control than would be offered by the broader field studies.

The water quality improvement study was a fairly intensive, two-year (1988-1990) effort to answer remaining questions about the water quality functioning of wetlands. Reinelt and Horner (in press) discuss its methods and findings.

The results of these various program components are being used to develop extensive guidelines for coordinated management of urban wetlands and stormwater. These guidelines are updated and refined as more information becomes available, a process that will continue throughout the program until the guidelines are finalized in 1996.

STORMWATER IMPACT STUDY DESIGN

The stormwater impact study is organized in relation to five areas that represent the major structural components of wetlands: (1) hydrology, (2) water quality, (3) soils, (4) plants, and (5) animals. These components are being monitored before, during, and after urbanization occurs in "treatment" wetlands. The object is to portray preexisting conditions, determine if they change with urbanization and modification of stormwater inflow, and assess the consequences of any changes.

For comparison, simultaneous monitoring is also being conducted in "control" wetlands, whose urbanization status is not changing much during the course of the studies. The watersheds of these controls range from no urbanization to relatively high levels, but they all share the attribute of relative stability in land use during these studies. The experimental design is thus the classic "before/after, control/treatment" scientific method approach. The use of control sites permits evaluation of whether documented changes in treatment wetlands are caused by urbanization or, possibly, by broader environmental conditions that affect all regional wetlands. Control wetlands are paired with treatment sites on the basis of size, water and plant zones, and vegetation community types. In recognition of the imperfect matches that occur in pairing natural systems, data analyses are performed for various groupings of sites and not just with respect to paired wetlands.

With the interest in long-term as well as short-term effects, the impact monitoring is being performed over an eight-year period. The years 1988 and 1989 generally provided the baseline data, while 1990 represented the early phase of urbanization in the treatment wetlands. Monitoring continued in 1993, generally shortly after a phase of building in the watersheds ended, and is resuming in 1995 to document effects taking longer to appear. Following this final year of monitoring, the plan is to define whatever new state of equilibrium is established in the treatment wetlands.

The stormwater impact study is being conducted in 19 wetlands in King County, approximately half of which are treatment sites and the remainder control sites. Figure 1 locates these 19 sites and four others, three in Snohomish County to the north, where special studies are occurring.

Figure 2 illustrates a conceptual framework for designing the specific sampling programs instituted under the stormwater impact study and analyzing and interpreting the resulting data. The two blocks on the left of the diagram represent the driving forces determining a wetland's character (Watershed Conditions and Wetland Morphology). Wetland morphology refers to form and structure and embraces shape, dimensions, topography, inlet and outlet configurations, and water pooling and flow patterns. The central block (Wetland Community Structure) represents the physical and chemical conditions that develop within a wetland and constitute a basis for its structure. Included are both quantity and quality aspects of its water supply and its soil system. Together these structural elements develop various habitats that can provide for living organisms, represented by the block at the upper right of the diagram. Biota will

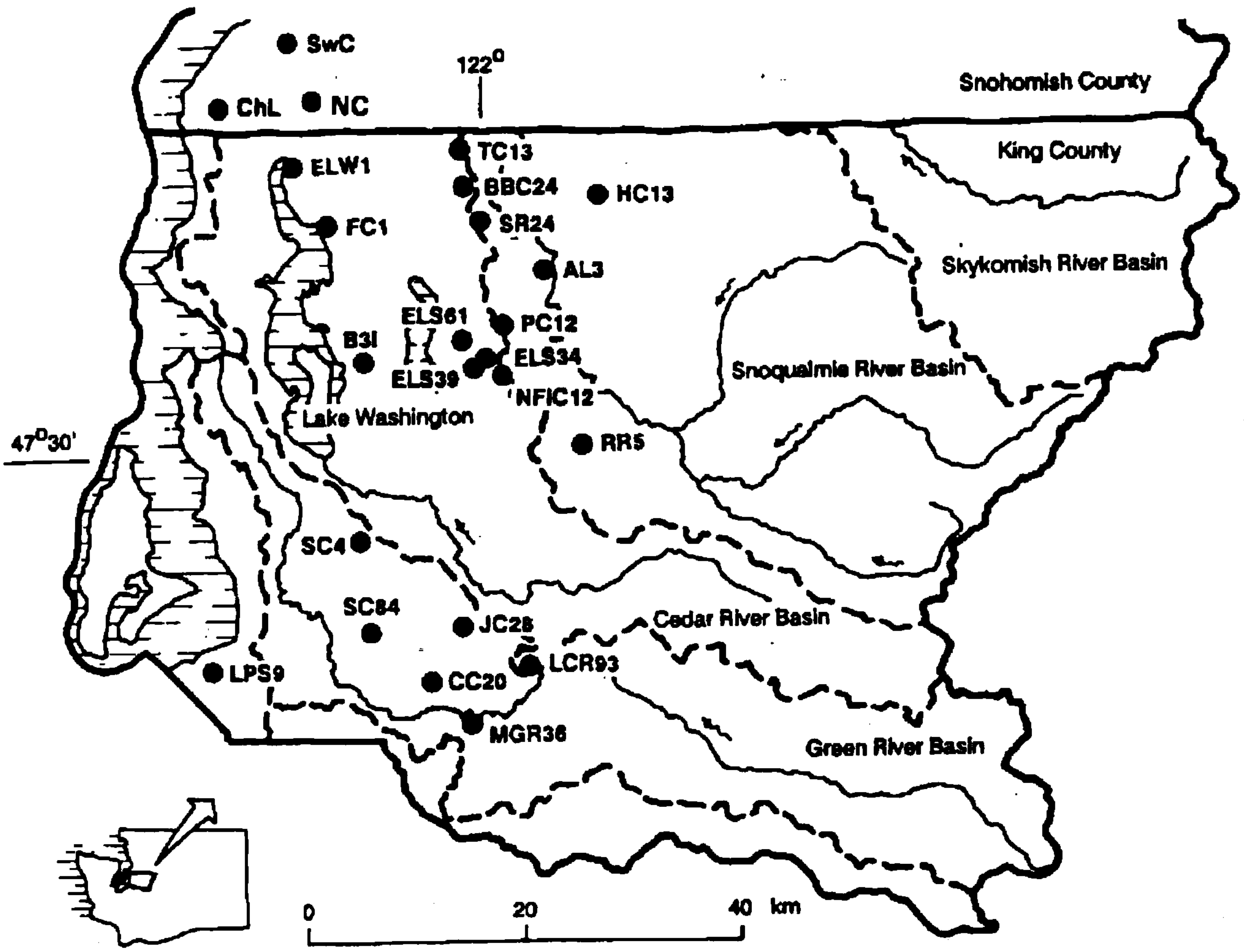

Figure 1. Puget Sound Wetlands and Stormwater Management Research Program study locations

respond depending on habitat attributes, as illustrated by the block at the lower left. It is a fundamental goal of the Puget Sound Wetlands and Stormwater Management Research Program to describe these system components for the representative wetlands individually and collectively.

Connecting lines and arrows on Figure 2 stand for interactions among the components. It is a second fundamental goal of the program to understand and be able to express these interactions, toward the ends of advancing wetlands science and the management of urban wetlands and stormwater. Expression could come in the form of qualitative descriptions, relatively simple conceptual models, or more comprehensive mathematical algorithms. The extent to which definition of these interactions can be developed will determine the thoroughness with which management guidelines and new scientific knowledge can be generated by this research program.

The papers that follow trace the major areas of progress to date in filling in the conceptual framework presented in Figure 2. The first paper in the series concentrates on the relationships between the driving forces and wetland hydrology and water quality. Following are two papers that discuss the plant species and vegetation community responses, the second of which also covers amphibian community development in relation to the habitat provided. The next paper examines the breeding success experienced by two amphibian species as a function of hydrologic and water quality conditions of their habitat. The final paper

summarizes the preliminary management guidelines developed from the results to date and how they are being used.

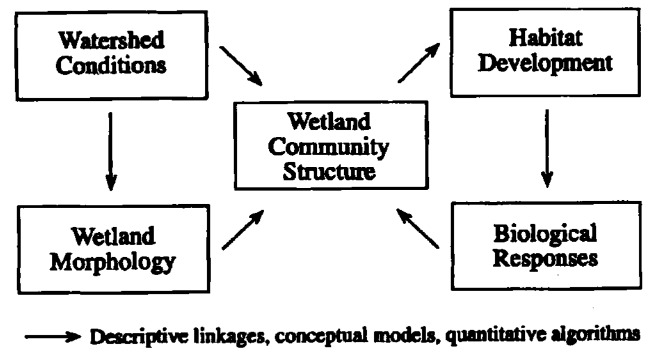

Figure 2. Puget Sound Wetlands and Stormwater Management Research Program experimental strategy

ACKNOWLEDGMENTS

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URBANIZATION EFFECTS ON WETLAND HYDROLOGY AND WATER QUALITY

Brian Taylor[1], Ken Ludwa[2] and Richard R. Horner[3]

INTRODUCTION

As outlined by Horner (1995) in the overview paper in this series, the Puget Sound Wetlands and Stormwater Management Research Program is pursuing better understanding of wetland ecosystems and improvements in managing them and the altered stormwater runoff they receive in urban settings through a systematic research strategy. This strategy is directed at attempting to describe the physical and chemical effects on wetland environments of changes in the watersheds contributing runoff to them, and then to describe biological responses to environmental conditions. This paper highlights the key findings to date with regard to wetland hydrologic and water quality relationships with watershed status. It sets the stage for three subsequent papers covering biological implications. Refer to Taylor (1993) and Ludwa (1994) for detailed coverage of the research presented here.

RESEARCH METHODS

Watershed Characterization

A geographic information system (GIS) was used to inventory land uses within the wetland's watersheds. Watershed boundaries were delineated from USGS 7.5-minute series topographic maps. Aerial photographs from 1989 were digitized into the ARC/INFO GIS (Reinelt et al., 1991), and the land uses were classified and mapped. More than 20 specific land use categories were identified. Wetland boundary delineations were based on wetland vegetation and open water visible on the aerial photographs. The GIS provided scale maps and tables showing the extent of each land use category.

Basin imperviousness was estimated from the land use inventory. Typical values of percent impervious area associated with each land use were found in the literature and used to estimate the total basin impervious area. The study distinguished between total impervious area (TIA) and effective impervious area (EIA). Total impervious area does not separate surfaces draining to soils from those discharging to the storm drain system. Effective impervious area consists only of impervious surfaces hydraulically connected to the storm drain system.

Land use parameters for 1993, used in conjunction with water quality data, were assessed similarly, but used manual methods rather than GIS. The GIS will be updated in 1995.

Wetland Hydrology and Morphology

Wetland water levels were monitored in 19 Puget Sound lowland palustrine wetlands from April 1988 through April 1991 (continuing in 1993, although not analyzed here, and again in 1995). An average of eight measurements per year were collected from crest-stage gauges, which record the peak water level at a location since the last gauge reading, and staff gauges, which provide instantaneous water levels (Reinelt and Horner, 1990). Two wetlands had much more frequent measurements.

Event water level fluctuation (WLF) represents the response of the wetland to a storm event, and was calculated as the difference in the peak and mean base water levels during a time interval. Sensitivity analyses showed that at least 10 WLF values should be used when calculating mean event WLF. Seasonal base water level fluctuation and length of the summer dry period were two other indices investigated

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(Taylor, 1993), but the emphasis was placed on mean WLF because of previously shown associations with biological thresholds (Azous, 1991; Richter and Azous, 1993).

Wetland morphology was characterized by two binary indices. Outlet constriction (OC) was classified as either low to medium (OC=0) or high (OC=1), depending on observed hydraulics at the outlet. Morphology (MRPH) represents flow channelization and was classified as predominately open water (MRPH=0) or channelized (MRPH=1).

Wetland Water Quality

Water samples were collected at 19 sites from 1988-1990, and again in 1993, using standard grab methods. The sampling schedule emphasized the wettest period of each year, when pollutant delivery to the wetlands is greatest, and the driest months, when pollutants tend to concentrate most. Sampling, sample handling, laboratory analysis and quality assurance measures were described by Reinelt and Horner (1990).

Statistical Analyses

A variety of statistical techniques were used in identifying relationships among watershed urbanization and wetland hydrology, morphology, and water quality. Microsoft EXCEL and SYSTAT were used for data processing and statistical analysis, respectively.

The normality of the WLF data was assessed using the Lillefors test, a variant of the Kolmogorov-Smirnoff test used to compare data distributions (Wilkinson, 1990). Data were not normally distributed at the 0.05 significance level, and subsequent analyses were non-parametric (not dependent on normally distributed data). Two types of tests were employed: threshold tests to determine levels of a specific watershed characteristic associated with a wetland response, and multivariate regression models to show how various wetland and watershed factors combine to affect wetland hydroperiod. Thresholds identified on scatter plots were tested with the Mann-Whitney or Kruskal-Wallis tests applied at a significance level of 0.05.

Multivariate least-squares linear regression models were developed to explain the variation in WLF between wetland-watershed systems. A forward step regression procedure was used, and the model fit was evaluated by the r^2 value and residual analysis. All (not mean) WLF and water quality values were used in the analyses, increasing the sample size and influence of data from sites with larger data sets.

Water quality data (for 12 parameters described below) were tested for normality. Each parameter's distribution was found to be non-normal; therefore, non-parametric tests were used for threshold analysis. The Mann-Whitney test (the non-parametric equivalent to the Independent Groups t-test) was used to test for significant differences in means, maxima, and minima of water quality parameters between various groupings of wetland sites.

For parameters that were shown to vary significantly between groups of sites, the means of the individual site means and extremes in each land use group were compared to criteria established by Reinelt and Horner (1990). These water quality criteria were based on regulatory standards, literature, and professional judgment.

Finally, multivariate linear regressions were performed to relate water quality mean and extreme values to watershed land use and wetland morphology.

RESULTS AND DISCUSSION

Wetland Hydrology in Relation to Watershed Conditions

Threshold responses

All of the wetlands were found to fit one of four patterns: (1) relatively stable base water level with slight fluctuations during storms, (2) relatively stable base water level with large fluctuations during storms, (3) fluctuating base water level with slight fluctuations during storms, and (4) fluctuating base water level with large fluctuations during storms (Reinelt and Horner, 1990).

Table 1 shows the factors associated with significant response in wetland WLF, threshold levels, and mean WLF within each threshold range. Urbanization increases imperviousness (TIA, EIA) and decreases forest coverage (%FOREST); these, along with highly constricted outlets and low wetland area relative to watershed area (WLA/WSA), are factors significantly associated with high WLFs. Figures 1 to 4 graphically illustrate relationships between watershed land uses and wetland event WLF threshold levels.

Regression models

While threshold analyses provide insight into factors important to wetland hydrology, the regression models reveal associations that account for the influence of multiple factors, providing a statistically based evaluation of the importance of each factor. Models were developed to explain WLF using both continuous predictor variables and binary variables. Table 2 shows the development of a model that uses two binary and one continuous variable. The model is typical in that the most important predictor is basin imperviousness, followed by OC and %FOREST.

Table 1. Threshold levels in the response of wetland event water level fluctuation

Factor	Range	Mean WLF (m)
Forested area	%FOREST = 0%	0.38
	%FOREST >= 14.7%	0.15
Total impervious area	2.0 <= %TIA <= 3.5%	0.10
	3.5 < %TIA <= 20%	0.18
	20% <= %TIA <=54.9%	0.48
Effective impervious area	0 <= %EIA <=12.9%	0.15
	14.6% <= %EIA <= 45.6%	0.48
Outlet constriction	Low to moderate	0.15
	High	0.34
Ratio wetland area: watershed area	0.005 <= WLA/WSA <= 0.042	0.30
	0.049 <= WLA/WSA <= 0.444	0.13

Table 2. Multivariate linear regression models to predict mean event water level fluctuation

r^2	Equation
0.73	WLF (m) = 0.146 + 0.330*(B-TIA)
0.80	WLF (m) = 0.119 + 0.288*(B-TIA) + 0.094*(OC)
0.85	WLF (m) = 0.185 + 0.216*(B-TIA) + 0.109*(OC) – 0.0012*(%FOREST)

Where: B-TIA is 0 for %TIA<=20, 1 for %TIA>20
OC is 0 for no to moderate constriction, 1 for high constriction

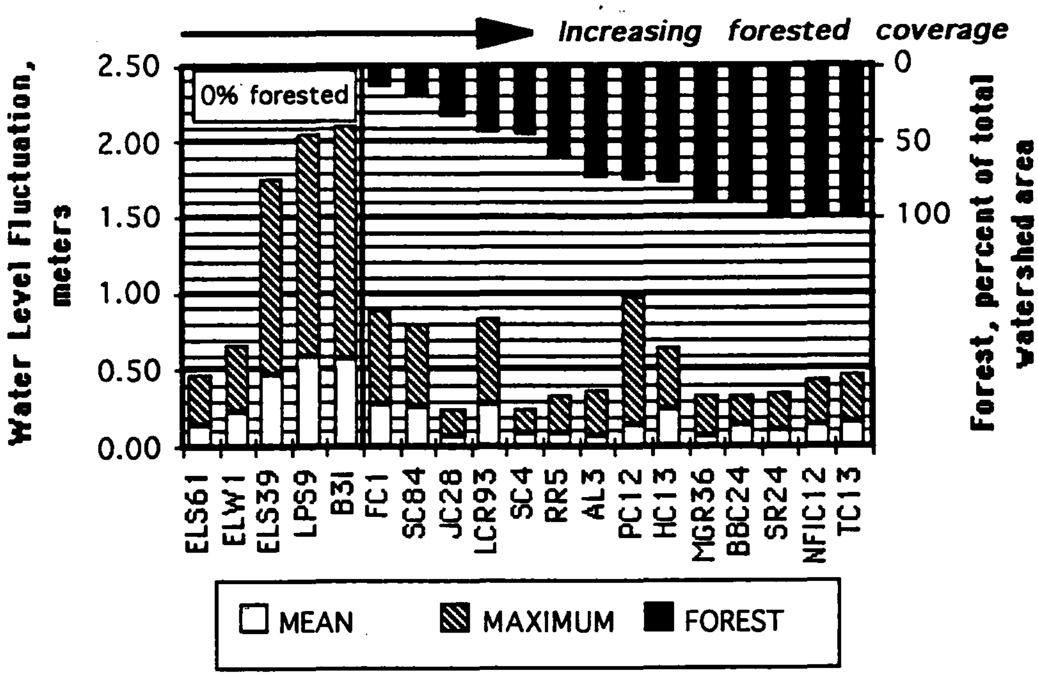

Figure 1. Relationship between event water level fluctuation and forested area

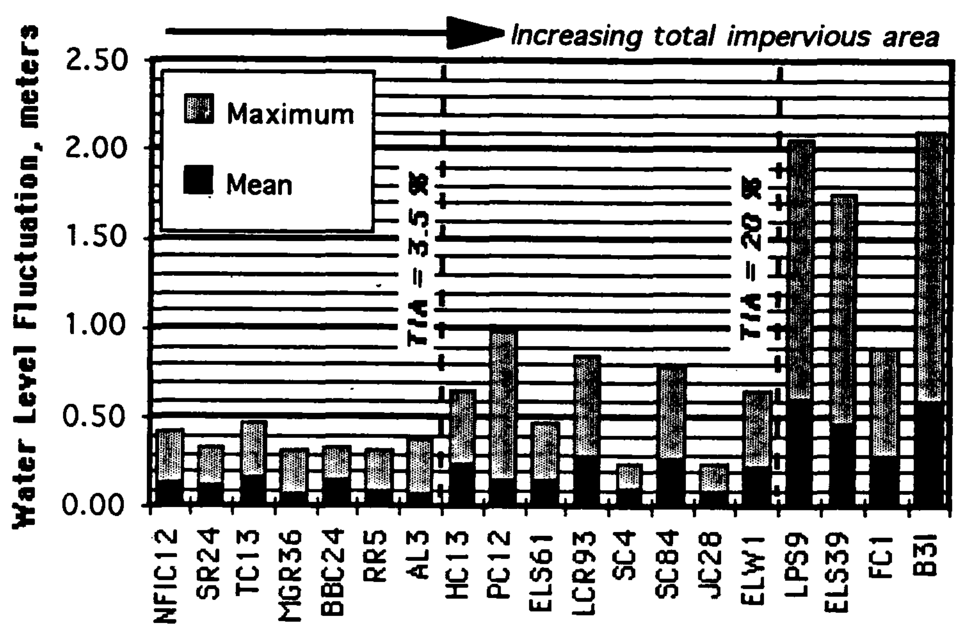

Figure 2. Relationship between event water level fluctuation and total impervious area

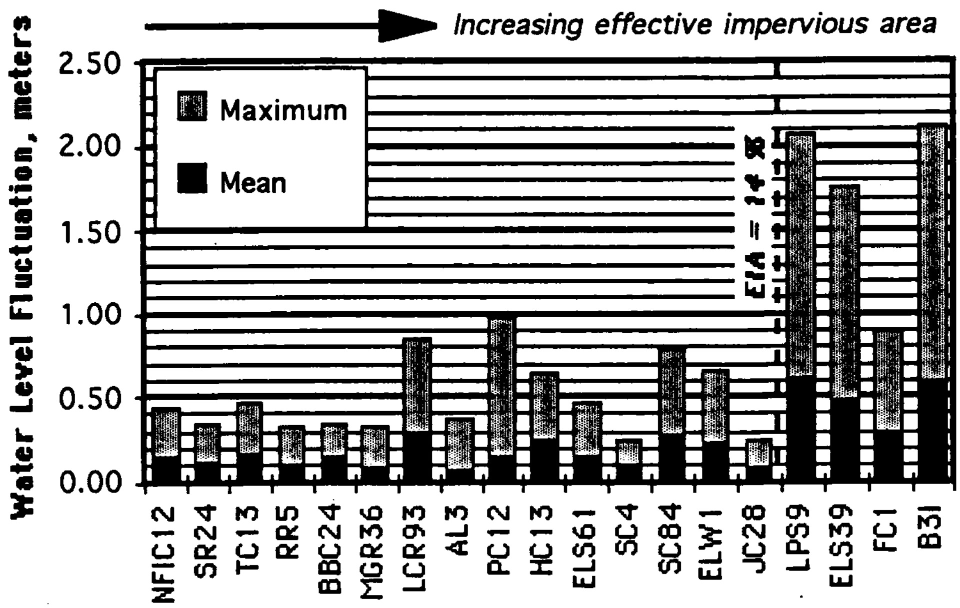

Figure 3. Relationship between event water level fluctuation and effective impervious area

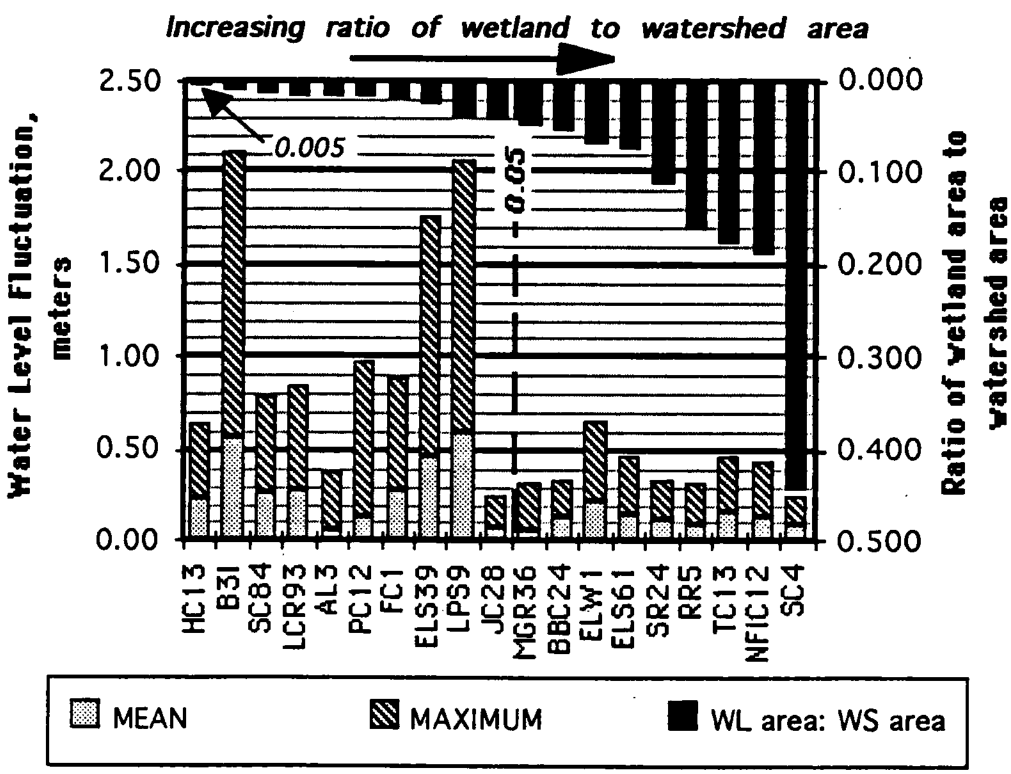

Figure 4. Relationship between event water level fluctuation and ratio of wetland to watershed area

The threshold analysis and regression models support the hypothesis that watershed land use is the most important influence on event WLF within a wetland. The two threshold levels of the %TIA predictor may reflect three states of watershed drainage system development: (1) forested with natural drainage and ample watershed storage, (2) low density residential with less storage and limited conveyance systems, and (3) medium density residential or greater with developed conveyance systems. The %FOREST predictor is inversely correlated to WLF. A regression model developed with continuous predictors showed that increasing TIA by 1 percent had the same effect on WLF as a 5 percent reduction in forested coverage.

Wetland Water Quality in Relation to Watershed Conditions

Threshold responses

A number of water quality parameters analyzed in this study were shown to vary significantly as watershed land use thresholds were exceeded. The pattern of variability suggests degradation of water quality (increased solids, bacterial indicators, etc.). Mean water quality degraded most significantly across thresholds for %FOREST, %TIA, ratio of the forested area:wetland area (FORA/WLA), and MRPH. The mean parameters that varied most notably across land use thresholds included conductivity (COND), total suspended solids (TSS), total zinc (TOTZN), dissolved oxygen (DO), and fecal coliforms (FC). Hydrogen ion concentration (ALOGPH) was somewhat responsive to the thresholds tested; results were inconsistent for nutrients.

Table 3 lists the water quality variables whose mean of site mean values exceeded criteria for the more urbanized groups of sites (those exceeding urban land use thresholds), while their mean of site means fell within criteria for the less urbanized group of sites. The variables that degraded most consistently as urbanization thresholds were exceeded (with the criterion value for each) were: COND, 100 (200) μS; TSS, 5 (10) mg/L; FC, 50 (100 and 200) colonies/100mL), and enterococci (ENT), 33 colonies/100mL. Criteria for the other variables listed are: chlorophyll a (CHLA), 10 μg/L; nitrate + nitrite-nitrogen (NO23N), 500 μg/L; ammonia-nitrogen (NH3N), 50 and 100 μg/L; soluble reactive phosphorus (SRP), 20 μg/L.

Table 3. Threshold levels in the response of wetland water quality variables

Land Use Parameter and Threshold Value	Water Quality Parameters Exceeding Criteria When Threshold Crossed
%FOREST (0%)	COND, TSS, CHLA, FC, ENT
%TIA (3.5%, 20%)	COND, TSS, NO23N, NH3N, FC, ENT
%EIA (13%)	COND, FC, ENT
WLA/WSA (0.05)	COND, ENT
FORA/WLA (8.0)	COND, TSS, SRP, ENT
MRPH (open water/channelized)	COND, TSS, CHLA, FC

Thresholds for %TIA and MRPH appeared to have the strongest effect on water quality minima. COND, TSS, and total phosphorus (TOTP) minimum values were most consistently related to land use thresholds. DO, ALOGPH, FC, and the remaining nutrients were also confirmed for a number of thresholds, but results were generally inconsistent.

Water quality maxima varied most consistently across thresholds for %TIA, %FOREST, FORA/WLA, and MRPH. COND, TSS, ALOGPH, TOTP, and TOTZN maxima were best related to land use thresholds. DO, FC, and the remaining nutrients were again inconsistently related to thresholds.

Threshold results suggest that for similar watersheds in this region, a maximum level of deforestation exists beyond which average wetland water quality in those watersheds will deteriorate to substandard conditions. Conversely, as long as some minimum amount of forested area is retained, it appears that average water quality will remain within recommended criteria. Because extremes in water chemistry are often the dominant factor affecting biological communities, threshold results for water quality maxima and minima are important as well. Maximum and minimum values for a number of relevant water quality variables demonstrate degradation across urbanization thresholds. The integrated result follows that, along with water level fluctuation, the entire range of a number of important water quality indicators is shifted significantly toward degradation.

Regression models

Multiple regressions using 1988-1990 land use and wetland morphology parameters as predictors significantly explained variance for 31 of 36 water quality parameter means, maxima, and minima. However, only the regressions for TSS, COND, and DO were confirmed by the 1993 data. Table 4 lists the amount of variance explained by the regressions for these parameters, along with the land use and wetland parameters present as predictors in the regression equations for each. Note that land use and wetland morphology parameters were present in the following forms: continuous (%), ratio, or binary (B-) (predictors assigned a value of 0 or 1, based on valid thresholds).

The signs of the regression coefficients indicated that increased watershed impervious area and deforestation consistently predicted degradation of all parameters except NH3N and SRP. Results of the regression equations also indicated that wetland morphology (MRPH) has a strong influence on wetland water quality. Wetland water quality was generally more degraded in highly channelized sites. For the regressions listed above, as well as those not confirmed by the 1993 data, binary predictor variables proved to be as effective as continuous predictors.

Table 4. Variables included and variance explained by verified multivariate linear regression water quality models

Variable	Variance Explained	Predictors
Mean DO	29%	WLA/WSA, B-EIA, B-FORA/WLA
Max. DO	32%	WLA/WSA, B-FORA/WLA
Mean COND	68%	%TIA, B-OC, B-MRPH, B-WLA/WSA
Max. COND	60%	B-MRPH, B-TIA
Min. COND	56%	B-OC, B-MRPH, B-WLA/WSA
Mean TSS	73%	B-FOREST
Max. TSS	69%	B-MRPH, B-FOREST
Min. TSS	48%	%FOREST, B-MRPH, B-WLA/WSA

CONCLUSIONS

Conclusions from the investigation of relationships among watershed conditions and wetland hydrology and morphology include: (1) mean and maximum WLF was significantly higher in wetlands when the percentage of impervious area in the watershed exceeded 3.5% and again when the percentage rose above 20%; (2) mean and maximum WLF was also significantly higher in wetlands whose watersheds had no

forested land cover compared to the other sites, which had at least 14.7% forest cover; (3) outlet constriction plays a substantial role in wetland WLF; and (4) the ratio of wetland area to watershed area strongly influences both WLF (significantly less when ratio > 0.05) and the length of the summer dry period.

Concerning water quality, COND, TSS, FC, and ENT exhibited the greatest differences between the most highly developed wetlands and those with no or moderate urbanization of their watersheds. Thus, these variables are probably the best indicators of degraded water quality conditions associated with urbanization. These data also showed some trends very similar to the hydrologic results: (1) COND, TP, and FC were significantly higher in wetlands when the percentage of impervious area in the watershed exceeded 3.5% and again when the percentage rose above 20%, although TSS, NO23N, and soluble reactive phosphorus (SRP) did not exhibit significant differences; (2) all but NO23N were significantly higher in wetlands whose watersheds had no forested land cover compared to the other sites, which had at least 14.7% forest cover; (3) all six variables tested had significantly higher means in relatively highly channelized wetlands than in those with low channelization, although extraneous factors probably color some of these findings; (4) outlet constriction and the ratio of wetland area to watershed area appear to play inconsistent roles in wetland water quality, unlike in hydrology; and (5) the ratio of forested area to wetland area strongly influenced all six variables (significantly higher when ratio < 7.2). The impervious area and forest cover thresholds defining significant differences in water quality are the same as found for hydrology. Using these data it was possible to calibrate, and in some cases verify, a number of linear regression models relating hydrology and water quality to several watershed and wetland morphological variables found to be important. Management analyses can begin to use these models, which will be subject to further verification with new, independent data.

ACKNOWLEDGMENTS

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VEGETATION RESPONSES TO CHANGING HYDROLOGY IN URBAN WETLANDS

Sarah Spear Cooke and Kern Ewing[1]

ABSTRACT

Wetland species and community types in the Puget Sound basin are specific in their tolerance for a given hydrologic regime (depth, duration and frequency of inundation). Different hydrologic regimes have been described as a result of four to six years of hydrologic monitoring in wetlands included in the Puget Sound Wetlands and Stormwater Management Research Program. Vegetation community and species requirements for these hydrologic regimes have been examined in order to characterize individual species requirements and to determine the ability of plants to adapt to changes resulting from urbanization.

Characterization of preferred hydrologic regimes suggests that many species found in the Puget Sound region are associated with hydrologic conditions that are different from their assigned indicator designation on the U.S. Fish and Wildlife Service plant-indicator status list. Further, the preferred hydrologic regime varies across the growing season, so that individual plant requirements during the early spring may be very different from those in the late summer.

Changes in the hydrologic regime as a result of urbanization pressures were found to be associated with shifts in plant richness, diversity, and productivity. Most native species are intolerant of high water-level fluctuations, a condition typical of urbanized wetlands. In addition, a plant's sensitivity to inundation (examining depth, frequency, and duration independently) during certain periods of the growing season is species-specific.

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AMPHIBIAN AND PLANT COMMUNITY RESPONSES TO CHANGING HYDROLOGY IN URBAN WETLANDS

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INTRODUCTION

Changes in land use often alter the hydrology, water quality and available habitat within a watershed. Freshwater wetland amphibian and plant communities can be affected, often undergoing changes in the number and distribution of species. Losses of plant species can affect the availability of food, cover and breeding habitat for animals. Losses of animal species can affect predation pressures and change food chain dynamics. The cumulative effect of these changes may reduce the diversity of native wetland species.

Previous research has shown a relationship between differences in water level fluctuation regimes and wetland community richness (Azous, 1991; Cooke and Azous, 1993; Taylor, 1993; Richter and Azous, in prep.). This paper will further examine some of the effects of changing hydrology on plant and animal communities in Puget Lowland palustrine wetlands. Moreover, the hydrologic characteristics of maximum and mean water level fluctuation are related to observed richness in amphibian and plant communities. Finally, individual amphibian and plant species are also examined for hydrologic preferences.

METHODS

Nineteen wetlands located throughout King County, Washington, were studied to determine the relationships between the richness and types of amphibian and wetland plant species found in a wetland and the hydrologic characteristics of maximum and mean water level fluctuation. The wetlands used for this study are described elsewhere (King County, 1988; Cooke et al., 1989). All wetlands are inland palustrine wetlands ranging in elevation from 50 m to 100 m above mean sea level and characterized by a mix of emergent, scrub-shrub, open water and forested vegetation classes based on the NWI vegetation classification system. Vegetation classes initially determined from aerial photographs were verified through site visits by botanists and soil scientists. Plots were sampled within each vegetation class, and the presence and coverage of individual plant species identified (Cooke and Conolly, 1990). Vegetation data used in this study were collected in 1989, 1990 and 1993.

Geographic Information System (GIS) analysis of USGS 7.5 minute series topographic maps was used to delineate watersheds, determine hectares of respective land uses and calculate percent of impervious area (Taylor, 1993). Watersheds were classified as having high or low urbanization depending on whether more or less than 20 percent of the land area was covered by impervious surfaces.

Hydrologists measured instantaneous water levels from staff gauges and peak levels from crest stage gauges eight times a year (Reinelt and Horner, 1990). Mean water level fluctuation (WLF) was the annual average difference between peak and instantaneous water levels for each reading (Taylor, 1993). Maximum WLF was the annual maximum difference between the annual peak and minimum instantaneous water level. Wetlands were also categorized based on WLF with low WLF equal to or less than a yearly average of 20 cm and high WLF greater than 20 cm averaged annually.

The distribution and relative abundance of amphibians was determined from autumn pitfall captures, from spring breeding censuses, and from opportunistic sightings during other field visits. Trapping occurred during the last two weeks of October in 1988 and 1989, after the start of the rainy season when soils were well saturated. Species sighted at a wetland but not captured were recorded as present (Richter et al., 1991).

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Data were analyzed with computer-based statistical applications programs. StatView (Abacus Concepts Inc., 1992) was used to develop scattergrams and perform all statistical analyses. The non-parametric Mann-Whitney U (MW) test was used to test the effects of changing hydrology on plant and amphibian species richness. The Fisher's Exact (FE) test was used to evaluate individual species' presence for different categories of mean and maximum water level fluctuation.

RESULTS

The relationship between mean and maximum water level fluctuation was evaluated for all the study wetlands and was found to be significant in wetlands with watersheds covered by more than 20 percent impervious surfaces. The scatterplot in Figure 1 shows regression lines for maximum and mean WLF in wetlands categorized by the level of development within their watersheds. The data indicate that, in more urbanized watersheds, the average change in wetland water depth will increase as the maximum water depth change increases. This is not the case in less developed watersheds, where there is little change in mean water level fluctuation even as the maximum increases. The average change in water depth increases relative to the maximum change in water depth in a developing watershed because the frequency of inundation to the maximum depth increases as the amount of runoff increases.

Both maximum and mean WLF were evaluated in the amphibian and plant analyses and showed consistently similar results. If a statistical relationship was present, in almost all cases, mean WLF was found to have the greater significance, probably due to its relationship with watershed urbanization. Consequently, we will report on mean WLF.

Amphibian Communities

Ten amphibian species were identified among all the wetlands surveyed. Northwestern salamander (*Ambystoma gracile*) and red-legged frog (*Rana aurora*) were found in 16 and 15 out of 19 wetlands respectively. The abundance and frequency of captures indicate they may be the most frequently occurring species within the Puget Lowland. At the same time, statistical analysis of the presence and absence of these species under high and low WLF regimes indicates that both species are significantly less likely to be found in high WLF wetlands (FE, $P < 0.04$).

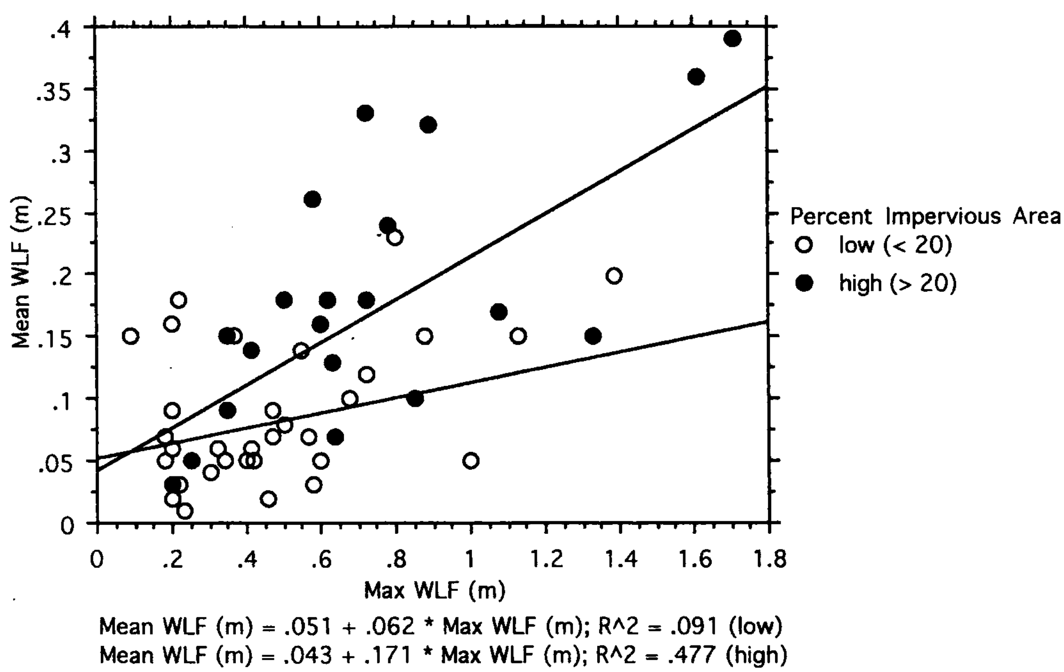

Figure 1. Mean WLF as a function of maximum WLF in watersheds with high and low watershed development

Pacific treefrog (*Pseudacris regilla*) was seen at 12 wetlands. Ensatina (*Ensatina eschscholtzii*) was the most frequently found terrestrial breeding species, being captured at 11 wetlands. Both the long-toed salamander (*Ambystoma macrodactylum*) and western redback salamander (*Plethodon vehiculum*) were seen in eight wetlands. These species were equally likely to be observed in wetlands with high as with low mean WLF conditions.

Three of the amphibian species were captured and sighted in insufficient numbers to analyze statistically. These included roughskin newt (*Taricha granulosa*), which was found in only four wetlands, all of them with low WLF, Western toad (*Bufo boreas*), captured in three wetlands, and Pacific giant salamanders (*Dicamptodon tenebrosus*), captured at two wetlands near streams.

Bullfrog (*Rana catesbeiana*), an introduced species to the Puget Lowland, were found at five wetlands. These included two wetlands adjacent to populated areas in addition to three at more remote locations.

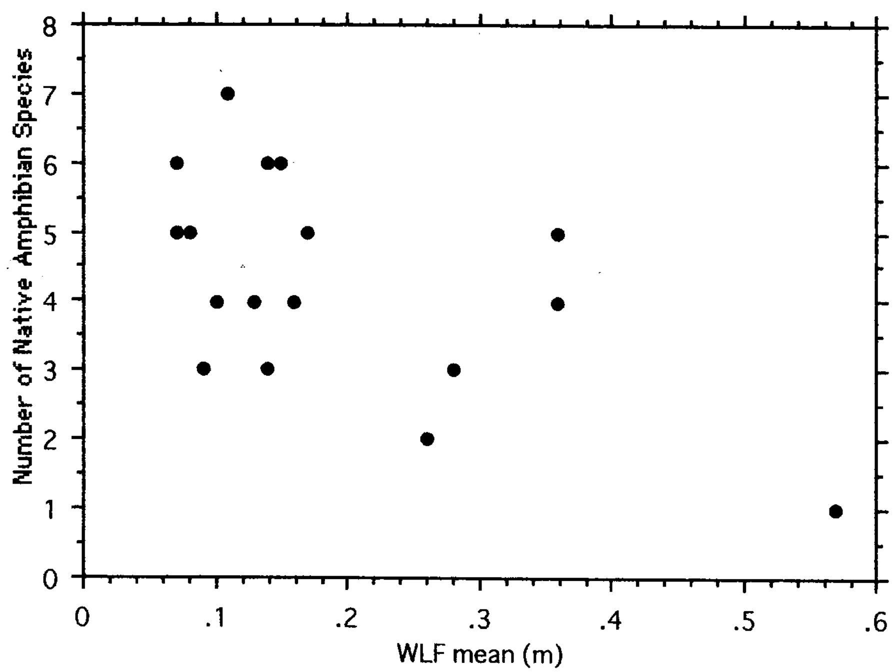

Figure 2. Amphibian richness as a function of mean WLF

Overall, the richness of amphibian communities was found to be lower in wetlands with WLF less than 0.2 m (Figure 2). Wetlands with greater WLF were significantly more likely to have low amphibian richness with three or fewer different species present (FE, $P = 0.046$).

Plant Communities

Emergent, scrub-shrub and forested wetland plant communities were studied individually to determine whether there were differences in the richness of wetland plant species that could be attributed to WLF regime. Total plant richness as well as combined facultative wetland and obligate plant richness were evaluated with the following results.

Plant richness in the emergent zones was consistently found to be sensitive to WLF regime. Emergent zones subject to mean WLFs greater than 0.2 m were ranked significantly lower in the number of plant species present (MW, $U = 55$, $P = 0.003$) than emergent areas with mean WLF less than 0.2m. Total plant richness and richness of facultative and wetland obligate plants were similarly affected (Figure 3).

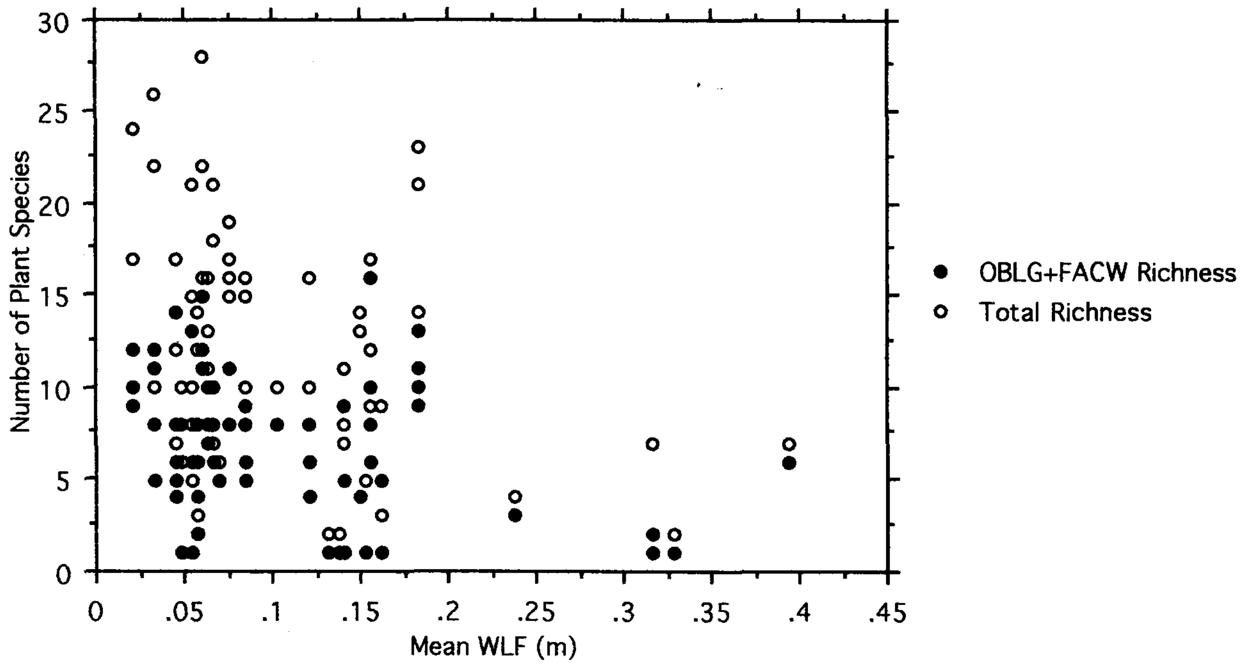

Figure 3. Total and combined FACW and obligate plant richness in the emergent zones as a function of mean WLF

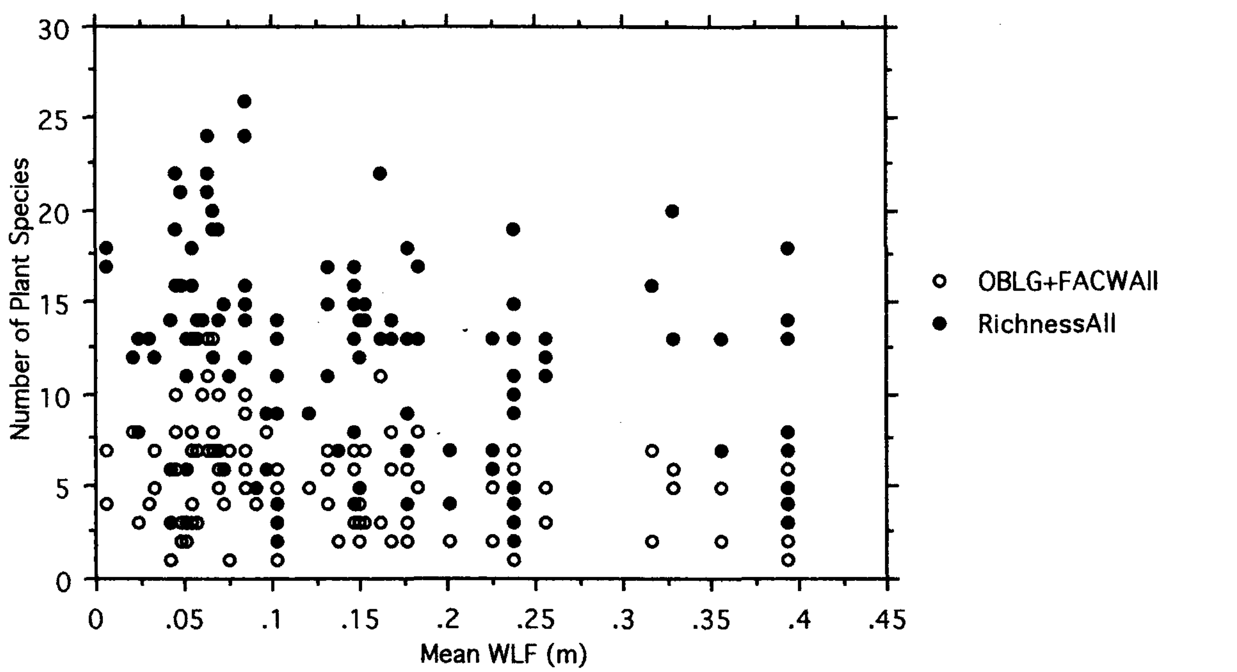

Figure 4. Total and combined FACW and obligate plant richness in the scrub-shrub zones as a function of mean WLF

The scrub-shrub zones also showed a significant difference in plant richness. Although total plant richness was affected (MW, U = 1043, P = 0.01), facultative wetland and obligate plant species were primarily affected (MW, U = 949, P = 0.002) (see Figure 4). Forested zones were also evaluated, but no significant break-points in tolerance to WLF regime were apparent.

Individual plant species were evaluated for their presence or absence in different WLF regimes as well as for the relative frequency of their occurrence within a range of WLF. Approximately 25 percent of all plants observed were found in less than two or three wetlands. Of the species remaining, one third were found almost exclusively in either a high or a low WLF condition. The remaining two thirds were observed equally in both conditions. Some of these results are summarized in Tables 1 and 2.

Several plants consistently found in wetland zones exposed to high WLF are highly competitive such as *Phalaris arundinaceae* (reed canary grass) and *Typha latifolia* (cattail). Other species such as *Bidens cernua* (nodding beggar-tick), *Myosotis laxa* (small flowered forget-me-not), and *Potentilla palustris* (marsh cinquefoil) were almost always found in mean WLFs less than 0.2 m. Some of the species listed as tolerant to low WLF are typically found in bogs, such as *Ledum groenlandicum* and *Ludwigia palustris*, and may be present due more to water chemistry rather than to fluctuation regime.

Table 1. Plants found most frequently in low WLF regimes

Species	Status	Form
Bidens cernua	facw+	h
Carex rostrata	obl	se
Eleocharis ovata	obl	se
Juncus bufonius	facw+	r
Ledum groenlandicum	obl	s
Lotus corniculatis	obl	h
Ludwigia palustris	obl	h
Myosotis laxa	obl	h
Potentilla palustris	obl	h
Puccinellia pauciflora	obl	g
Scirpus cyperinus	obl	s
Sparganium emersum	obl	h
Sphagnum spp.	obl	f
Thuja plicata	fac	t
Veronica scutellata	obl	h

Form:
h = herbaceous
s = shrub
se = sedges
f = ferns, horsetails, allies, and mosses
r = rushes
g = grasses
t = trees

Ratings:
low = Species presence significant at < 10 cm WLF
high = Species presence significant at > 10 cm WLF

DISCUSSION

The depth, duration and frequency of inundation of water within a wetland describes its hydrologic regime. Mean annual WLF is a measure of the frequency of inundation in a hydrologic regime and may result in corresponding responses in the biological community.

Findings indicate that amphibian richness is statistically associated with the WLF regime of a wetland. The two most commonly found species, Northwestern salamander and red-legged frog, were significantly absent from wetlands with high WLF. Pacific giant salamander was observed rarely, but that was expected as it is more commonly found near fast-moving streams than wetlands. Two other species, roughskin newt and Western toad, were observed rarely and then only in wetlands with low WLF. The case of roughskin newt is particularly disturbing as this species has historically been reported to be the most common and abundant salamander in western Washington (Nussbaum et al., 1983).

Table 2. Plants found most frequently in high WLF regimes

Species	Status	Form
Cornus stolonifera	facw	s
Equisetum arvense	facw	f
Equisetum telmateia	obl	f
Lysichitum americanum	obl	h
Oenanthe sarmentosa	obl	h
Phalaris arundinaceae	facw	g
Ranunculus repens	facw	h
Rubus discolor	facu	s
Salix lasiandra	facw+	s
Scirpus microcarpus	obl	s
Solanum dulcaria	obl	h
Spirea douglasii	facw	s
Stachys cooleyae	facw	h
Typha latifolia	obl	h

It is possible that water level fluctuations may thwart successful spawning, embryogenesis or larval survival of lentic breeding species, the dominant water-breeding amphibian, in Puget Lowland wetlands. Both Northwestern salamander and red-legged frog lay large egg clutches attached to emergent vegetation within the water column. These egg clutches may be sensitive to frequent desiccation from fluctuating water levels in developing watersheds, affecting spawn survivorship.

Other factors that may account for the reduced diversity of amphibians in urban wetlands not evaluated here include poor water quality, habitat loss and fragmentation, and predation. Although the study wetland's concentrations of heavy metals including zinc, lead, cadmium and copper, and other commonly assessed water quality characteristics such as nitrite, pH, and alkalinity are reported (Reinelt and Horner, 1990) to be at concentrations below documented levels for deformities and mortality (Power et al., 1989), sublethal impacts from low levels of exposure or from the synergism between water quality parameters could be a chronic cause for reduced richness (Platin, 1994; Platin and Richer, this proceedings).

Habitat losses and isolation may also be important in accounting for decreased amphibian richness. Migrating species are often constrained by subdivisions, transportation corridors and other urban environments.

Plant community structure also showed some responses to WLF. Plants in forested zones did not show a response to WLF and therefore may be more protected from impacts associated with high WLF than species more typical of emergent and scrub-shrub zones. The hummocky structure of forested wetlands produced by the large amount of downed and rotting logs may provide some protection for many understory plants. The hummocks and downed material may also help to moderate water level changes by absorbing water and releasing it slowly. On the other hand, emergent zones often lack such structural elements and may be more vulnerable to impacts resulting from increased incidence of short-term water inundation. Field observations of wetlands exposed to high WLF regimes show they are frequently dominated by a few species, often a mix of willow and *Spirea douglasii* (spirea), or cattail and grasses with little understory. Repeated inundation may act as a disturbance factor favoring the survival of these more aggressive species.

For the majority of plant species surveyed and found in sufficient numbers to test, the ranges of WLF do not appear to be a factor in their presence or absence. Yet plant communities tend to be simpler in high WLF wetlands. This suggests that changing hydrology in urban watersheds may alter the competitive abilities of plants, benefiting more tolerant species while acting as a stress on others.

Management of WLF regime in urbanizing wetlands may be critical to maintaining diverse amphibian and plant communities. Some losses of amphibian species may already be occurring in Puget Lowland wetlands due to land-use changes and stormwater management practices. Whenever we can maintain or only moderately increase the pre-development frequency of peak flows occurring in a wetland, it will likely benefit both amphibian and plant biodiversity.

ACKNOWLEDGMENTS

Support for this research was provided by the Washington Department of Ecology to the Puget Sound Wetlands and Stormwater Management Research Program and King County Surface Water Management. We would also like to kindly thank Kern Ewing, Sarah Cooke, Rich Horner and Lorin Reinelt for providing very helpful comments.

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AMPHIBIANS AS BIOINDICTORS OF STRESS ASSOCIATED WITH WATERSHED URBANIZATION

Teresa J. Platin[1] and Klaus O. Richter[2]

INTRODUCTION

Traditional water quality bioindicators include protozoa, phytoplankton, zooplankton, macro-invertebrates and fish. More recently amphibians, and especially their eggs, have been identified as bioindicators because of their sensitivity to a wide variety of environmental perturbations (Power et al., 1989). The bulk of the amphibian bioindication literature describes lethal concentrations of pesticides, metals, and water quality contaminants on adults and eggs under laboratory conditions (Power et al., 1989), and a formalized standard laboratory bioassessment procedure on African clawed frog eggs, *Xenopus laevis*, FETAX, now has wide acceptance (Bantle et al., n.d.; ASTM, 1991). Recently, this method has been applied regionally to determine whether irrigation drainwater may be responsible for the disappearance of native frogs from the Klamath Basin National Wildlife Refuge in Oregon. Results to date support the hypothesis that agricultural runoff is causing egg mortality and embryo deformities in African clawed frogs (Boyer, 1993), and that basin runoff is responsible for the decline of once common native species.

Only a few studies have investigated water quality impacts on native amphibians breeding in their natural habitats. Two of the more informative ones include a study of the effects of pond chemistry on egg survival in two synoptic salamanders *(Ambystoma jeffersonianum* and *A. maculatum)* in Massachusetts (Jackson and Griffin, 1991) and a study of heavy-metal-laden mine tailings on bullfrog *(Rana catesbeiana)* eggs in western Montana (Linder et al., n.d.). Collectively these papers show relationships between several water quality parameters and egg survivorship, and they show that field observations provide confirmation of controlled laboratory findings.

In the Pacific Northwest several recent reports have documented a correlation between decreasing amphibian richness and increasing urbanization of a wetland's watershed (Azous, 1991; Richter and Azous, in review). It is hypothesized here that the lower numbers of amphibian species at some wetlands may be caused by both poor water quality and unfavorable hydrology, which in turn lowers egg survivorship. The lower numbers furthermore suggest that amphibians, and particularly their eggs, may be used as bioindicators of wetland health. The focus of this paper is the physio-chemical impacts on survivorship, whereas a companion paper (Richter and Roughgarden, in prep.) will describe the hydrodynamic and hydrologic impacts on amphibian breeding.

OBJECTIVE

The objective of this study was to investigate the relationship between amphibian breeding success and physio-chemical water quality characteristics of palustrine wetlands of the Puget Basin. This was accomplished by developing a red-legged frog *(Rana aurora)* and Northwestern salamander *(Ambystoma gracile)* egg survivorship model based on significant water quality parameters.

FIELD METHODS

Amphibian Monitoring

Red-legged frog and Northwestern salamander breeding, oviposition and egg survivorship were monitored concurrently with the sampling and analysis of water and soil parameters. Naturally spawned eggs of red-legged frogs were monitored at wetland TC13 and Northwestern salamander egg masses at

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wetlands LPS9 and ELS61. At BBC24 Northwestern salamander and red-legged frog partial clutches of 10-20 eggs were contained within 9x12x2 cm 500-micron mesh nylon enclosures clamped to stainless steel rods. Wetland locations and a complete hydrologic and biologic description of each are provided in Platin (1994).

Each wetland was completely searched for spawn, and eggs were individually numbered as they appeared. To minimize disturbance at naturally found oviposition sites, all egg masses were censused in the water. The number of eggs in Northwestern salamander clutches was determined by counting all eggs whenever possible or by doubling counts made on half the eggs on one side of attachment stems. Red-legged frog eggs were estimated by counting all eggs in a clearly definable sub-section of the spawn, measuring the length, width and breadth of the entire spawn, and then extrapolating the counted eggs to the entire clutch. Egg estimates were confirmed by a second biologist and refined by repeated counts of clutches during subsequent field visits. Fertility was determined by examination of a subset of at least five eggs from each spawn with a hand lens. If eggs passed through early cleavage, the clutch was counted as fertile. Mortality was established by counting molded eggs and eggs displaying retarded development. Percentage mortality was determined by dividing the number of affected eggs by the total number of eggs estimated within each clutch. Egg survivorship was monitored between February and June 1993. Eggs were censused once at ELS61 and twice at TC13. Because of the specialized nature of the experiments at BBC24 and LPS9, these sites were censused weekly (16 times) and six times, respectively.

Water Level Fluctuation

Water surface levels were monitored at permanent staff and crest gauges, and these readings were used to calculate water level fluctuations (WLFs), following the formula developed by Taylor (1993) in which WLF = Crest Measurement – 0.5*(Staff Measurement + Previous Visit Staff Measurement).

Physio-Chemical Parameters

Water quality was sampled seven times at amphibian egg concentration sites from January through July 1993. From grab samples, the following parameter levels were determined: temperature (TEMP), pH, dissolved oxygen (DO), conductivity (COND), turbidity (TURB), total suspended solids (TSS), fecal coliforms (FC), ammonia (NH3), nitrite+nitrate ($NO2+NO3^-$), orthophosphates (ORTHO-P), total phosphorus (TP), aluminum (Al), copper (Cu), iron (Fe), lead (Pb), zinc (Zn), calcium (Ca), magnesium (Mg), total organic carbon (TOC), dissolved organic carbon (DOC), tannins/lignins (TL), and total petroleum hydrocarbon (TPH). Soil cores were collected during one visit to each wetland in mid-spring, 1993. Cores were analyzed to determine levels of microtox (MTOX), pH (SpH), oxidation reduction potential (REDOX), total nitrogen (TN), total petroleum hydrocarbon (STPH), total phosphorus (STP), total volatile solids (TVS), particle size distribution (PSD), aluminum (SAl), arsenic (SAs), cadmium (SCd), chromium (SCr), cobalt (SCo), copper (SCu), lead (SPb), lithium (SLi), nickel (SNi), gold (SAu), thallium (STl) and zinc (SZn).

DATA ANALYSIS

General

Several processing and statistical measures were used to develop models relating physio-chemical parameters to egg survivorship. In laboratory analyses yielding physio-chemical parameter levels less than the method detection limit (MDL), the reading was represented by half of the MDL, a commonly used censored data replacement. Missing data due to collection or lab errors occurred infrequently; therefore, those sampling runs containing missing data were eliminated from the analyses without substantially degrading the size of the data set. All parameters but copper were used in the final data analysis. Copper was eliminated because of levels below the MDL in more than 50% of the samples taken at each site. Based on low detectability, lead, zinc and aluminum were eliminated from the data set at BBC24, and zinc was excluded from the analysis at ELS61.

Principal Components Analysis

To ensure statistical rigor in the regression models, the independent data set was first screened to eliminate those variables not explaining a significant amount of variance. By reducing the number of variables and subsequently combining them into two or three factors, a linear regression model could more easily and accurately be constructed. The application of this process, called principal components analysis (PCA), is described in depth in Platin (1994).

Multiple Linear Regression Models

Step-wise multivariate linear regression models were developed to investigate the relationship between percent mortality in Northwestern salamander and red-legged frog eggs, and water and soil parameters. Probability (p-values), r^2-values, standard errors, tolerances and regression coefficients were considered in selecting bioindication models. The significance of regression equations is reported here in terms of r^2-values (the closer to 1.0, the greater the correlation), p-values (<0.05 = this study's definition for statistical significance) and standard errors (the smaller the better).

Data Fitting

Biological and water quality monitoring occurred at different time intervals, therefore, a time-weighted average was used to convert the latter data to approximations of ambient conditions during the biological monitoring period. The lack of extreme degradation in the wetlands during the biological monitoring periods alleviated concern over "smoothing out" extremes capable of causing acute mortality in the amphibian embryos.

RESULTS

General Physio-Chemical Summary

The quality of the water sampled at the four wetland sites was noteworthy for the following extremes: TC13 was the most acidic site; ELS61, TC13 and LPS9 had elevated water aluminum and iron levels; and LPS9 exhibited chronically low levels of dissolved oxygen. The soils all exhibited relatively high nutrient and metal levels, suggesting that these wetlands are a sink for their contributing basins' contaminants. Perhaps the most significant difference across the wetlands was fluctuating water levels. The wetlands in the basins with the lowest ratios of total impervious area to wetland area (BBC24, TC13) had the lowest fluctuations in water level. The wetlands in the more urbanized basins (ELS61 and LPS9) exhibited higher WLFs. It should be noted that WLFs at BBC24 were also moderated by a series of beaver dams.

Principal Components Analysis

Separate sets of water and soil principal components (PCs) were statistically identified to reduce the size of the physio-chemical data set. These PC groupings are as follows:

- Water Quality/Hydrology PC1: TP, TSS, Pb, Zn, Al, Fe, TOC, DOC, WLF
- Water Quality/Hydrology PC2: Cond, Ca, Mg, pH
- Soil PC1: SpH, STPH, SAl, SCr, SCo, SLi, SNi, SAg, STl
- Soil PC2: SAs, SCd, SCu, SPb, SZn
- Soil PC3: Sand, Silt

These PCs are valuable groupings of the many variables comprising the original data set. They are useful for identifying the parameters most likely to have an impact on the analyses. The surrogate variables PC1 and PC2 appeared in several of the successful regressions; however, collinearity or another internal error plagued the combined use of these PCs in a single regression. It is likely that because the PCs were created from the entire database for the whole wetland system, they did not translate well to the smaller data sets used at the individual sites. Had there been three or four times the number of physio-

chemical sampling occasions at each wetland site, the data sets may have been better suited to individual PC analyses. The individual analyses may well have indicated that other combinations of parameters were contributing more significantly to the variance in the data. Because this was recognized during the development of the regression models, the models were rigorously tested using all of the original parameters and several transformations of these variables.

BBC24: Water Quality and Hydrology Models

In the following regression results, "FMORT" represents red-legged frog egg mortality, "SMORT" Northwestern salamander egg mortality, and "MORT" is the combined mortality determined during the spring census of all the project wetlands. The normal data set as well as the following transformations of the data were tested: natural logarithm (ln), square root (sqrt) and inverse (inv).

Table 1 summarizes the significant relationships between amphibian egg mortality and water parameters developed during the monitoring period at BBC24.

Table 1: Biomonitoring regression equations for BBC24

Regression Equation	r^2-value	p-value	Standard Error
ln(FMORT)=1.147-0.418*(PC2)	0.820	0.002	0.809
ln(FMORT)=1.147+0.442*(PC1)	0.770	0.004	0.914
ln(FMORT)=-2.505+1.792*(lnTPH)	0.920	0.000	0.538
inv(SMORT)=0.144-0.047*(PC1)	0.540	0.006	0.120
inv(SMORT)=15.215-1.093*(sqrtCOND)-3.626*(sqrtTL)-0.502*(sqrtTPH)	0.923	0.000	0.055
inv(SMORT)=0.063+0.605*(invTPH)	0.655	0.001	0.088

Other noteworthy correlations (r^2>0.750 and p<0.010) were developed between ln(FMORT) and the following individual parameters: invTSS (negative correlation), lnTURB, lnTP, sqrtTURB, sqrtTPH, sqrtNH3, sqrtTP, lnTSS, lnMg (negative correlation), lnCa (negative correlation) and lnCOND. Additional relationships for SMORT were not as strong (r^2>0.500 and p<0.025), but are noted as follows because they support the use of PC1 in the invSMORT relationship: FC and WLF (combination) to SMORT and lnDOC and lnTSS (combination) to sqrtSMORT. Two other relationships not related to PC1 also resulted with moderate significance. The combination of invNH3 and invCOND, as well as the individual parameter invTL, were correlated to invSMORT.

BBC24 Discussion

Although the application of PCs is best suited to larger data sets, the results here show that there is a basis for their use in investigations of this size. The most significant PC results occurred at BBC24. Here the natural log of frog embryo mortality was positively correlated to PC1 and negatively correlated to PC2. This suggests that the variation of TP, TSS, Pb, Zn, Al, Fe, TOC, DOC and WLF (parameters in PC1) and COND, Ca, Mg, and pH (parameters in PC2) are significant factors in the incidence of red-legged frog egg mortality. While none of the PC1 metals registered on an individual basis at this site, TP and TSS were positively correlated to mortality in regression equations using all parameters. Although not known to directly affect biota, high levels of TP are indicative of urbanization and can lead to increased eutrophication of freshwater wetlands and can indirectly affect the viability of amphibian eggs. TSS, a parameter impacted by land use and soil type in a watershed, is a physical irritant to eggs and can coat the outer membrane, leading to suffocation. Elevated TSS quantities can also reduce the dissolved oxygen content in water (due to the decomposition of organic suspended solids) and reduce the clarity in a water body, adversely affecting development.

Red-legged frog embryo mortality correlated to fluctuations in the surrogate variable PC2. Because the mortality percentage is negatively correlated to this surrogate variable, it is likely that Ca, Mg and pH levels were more strongly affecting the mortality than conductivity itself. The natural logs of Ca and Mg were more significantly correlated to mortality than the natural log of conductivity. Higher levels of all three of the former variables can be beneficial in the range of values found at the project sites, while high levels of conductivity can be indicative of detrimental conditions in a watershed. Ca and Mg contribute to water hardness, which in turn reduces the toxicity of heavy metals (Snoeyink and Jenkins, 1980). Amphibian embryos, sensitive to acidity, are aided by higher levels of the pH-buffering cations of Ca and Mg (Freda and Dunson, 1986). pH itself is important in determining the viability of amphibian embryos. Previous studies have concluded that at low pHs (those below 5.0 for most amphibian species), embryos can develop curling defects, undergo delayed embryogenesis, have greater susceptibility to infections and exhibit an increased incidence of death. The relationships between the PCs and mortality were much weaker for Northwestern salamander eggs than for red-legged frog eggs.

Other results independent of the PC variables at BBC24 present a strong case for the use of red-legged frogs as bioindicators. Embryo mortality was highly representative of the levels of TPH found at BBC24. Very little research has documented the effects of TPH on amphibians, but high levels of TPH are known to cause acute and/or chronic responses (USEPA, 1986) and are generally the result of watershed urbanization. Of the other parameters significantly correlating to embryo mortality in red-legged frogs, only TURB and NH3 have not been addressed here. Turbidity is similar to TSS in source and effect. The un-ionized form of ammonia, NH3, is the toxic form of ammonia in water (USEPA, 1986), but no direct or indirect effects of NH3 on amphibians were found in the literature.

The most promising biomonitoring finding from Northwestern salamander egg survivorship studies at BBC24 was the correlation showing that salamander embryo mortality could be used as a predictor of high TPH levels. Mortality was also correlated to the pair, FC and WLF, but the overall relationships between mortality in Northwestern salamanders and water quality at this site were not as strong as those for red-legged frogs.

LPS9: Water Quality and Hydrology Models

The attempt to correlate either PC1 or PC2 to Northwestern salamander egg mortality at LPS9 provided no significant relationships. Two individual parameters did, however, yield useful regressions, as shown in the following table.

Table 2: Biomonitoring regression equations for LPS9

Regression Equation	r^2-value	p-value	Standard Error
sqrt(SMORT) = -16.406+0.414*(COND)	0.959	0.021	0.503
sqrt(SMORT) = 47.536-27.977*(sqrtDO)	0.891	0.056	0.823

The only other significant correlations at this site also involved conductivity; sqrt(SMORT) was correlated to sqrtCOND, and lnSMORT was correlated to lnCOND, both with $r^2 \geq 0.950$ and $p \leq 0.025$.

LPS9 Discussion

The number of amphibian species found at Puget Sound wetlands has been strongly negatively correlated to wetland conductivity (Azous, 1991). It is hypothesized here that one mechanism by which this reduced species richness may occur is the detrimental effect of conductivity on egg survival, as suggested by the correlations. Interestingly, conductivity has no known health significance (WHO, 1979). Therefore it is probable that the conductivity itself is not the causative agent in embryo mortality but rather a surrogate of other harmful conditions, which at this time remain unidentified.

Dissolved oxygen levels were chronically low at LPS9. Low dissolved oxygen is often a consequence of pollutant loading in a wetland. Because they are fairly static systems, wetlands have little opportunity to replenish DO, except through photosynthesis (Hitchman, 1978). Besides the influence of urbanization on DO at LPS9, low photosynthetic replenishment rates may have existed due to the lack of emergent vegetation. (The vegetation had been removed prior to spawning and replaced with surrogate attachment sites as part of a concurrent study of breeding preference. For details, see Richter and Roughgarden, in prep.; or Platin, 1994.)

The use of Northwestern salamander eggs as bioindicators of increased conductivity, lowered DO levels and overall watershed degradation is supported by the survivorship results at LPS9.

Spring Census: Water Quality and Soil Characteristics Models

The spring census models used both the water quality and the soil characteristics data from each of the wetlands monitored. The PC surrogate variables were developed to characterize the variance in the entire wetland system; therefore, they seemed better suited for use in the spring census regression equations than in any individual wetland evaluations. This was not entirely true, however, because the biological monitoring was for only one event at each site. Another important consideration in the analysis of the spring census data is that three of the wetlands supported natural populations of Northwestern salamanders, while the fourth, TC13, supported only red-legged frogs. All four wetlands were used in the models, with the intent to describe the factors that contribute to *amphibian* embryo mortality. Regardless of specific species tolerance differences, the mortality across the four wetlands followed a very distinct pattern. The least urbanized watersheds exhibited lower mortalities than the more urbanized watersheds.

Amphibian embryo mortality across all of the sites was significantly correlated to two of the soil PCs (SPCs), but neither of the water PCs. It was also strongly related to WLF. These relationships are shown in Table 3.

Table 3: Biomonitoring regression equations for spring census evaluation

Regression Equation	r^2-value	p-value	Standard Error
(MORT)=9.255+2.103*(SPC2)	0.943	0.029	3.342
ln(MORT)=1.513+1.626*inv(SPC3)	0.931	0.035	0.702
(MORT)= -2.642+1.628*(WLF)	0.985	0.007	1.705

Spring Census Discussion

The regression equation featuring SPC2 shows that amphibian mortality responds to increases in the individual metals represented by this surrogate. High soil metal levels are indicative of watershed urbanization and are known to be toxicants to many species of amphibians. Early life stages are sensitive to arsenic toxicity (USEPA, 1986), and cadmium is known to inhibit the development and hatching success of fish larvae (often considered similar in toxicological response to amphibian larvae). Copper, lead and zinc exhibit varying degrees of toxicity to the young of several species, but no direct mention in the literature was found of the effects on amphibian embryos. Soil zinc levels were negatively correlated to amphibian species richness in an earlier study (Azous, 1991).

Embryo mortality has been shown here to be indicative of the constituents of SPC3, sand (positive PC component) and silt (negative PC component). As watersheds become urbanized, finer particles are eroded due to increases in vegetation clearing and construction. The equation above shows mortality increasing as SPC3 decreases, i.e., as the amount of finer particles (silt and clay) increases.

The investigation of the individual parameters contributing to mortality showed that WLF can be positively correlated to embryo mortality. This correlation supports the idea that there are optimum water

levels and fluctuations for embryogenesis, as determined in the companion study (Richter and Roughgarden, in prep.; Platin, 1994).

CONCLUSIONS

The periodic monitoring of the embryos at BBC24 and LPS9, as well as natural spring census data gathered there and at the other two sites, provided valuable information on embryo responses to 25 water and 20 soil characteristics. The following conclusions were drawn from the results of the mortality monitoring:

Statistical Findings

1. The PCs resulting from this analysis are an excellent stand-alone characterization of the parameters causing variance in the four project wetlands.
2. PC analyses can be a useful tool to determine which parameters in a data set are significantly affecting variance. Although often corroborated by individual parameter testing in the regression analyses, the application of PCs in this study may have been limited by the translation of an overall wetland system characterization to smaller site-data sets.
3. Although relationships were derived from studies at four sites with relatively few visits, studies at 10 wetlands for six weeks would likely yield better correlations.

Bioindication Findings

1. Native amphibians can be used as biomonitors of wetland conditions and stresses associated with urbanization.
2. Red-legged frog embryo mortality can be better predicted using principal component surrogate variables than Northwestern salamander embryo mortality.
3. Red-legged frog embryo mortality can be correlated to more individual stresses than Northwestern salamander embryo mortality.
4. Both red-legged frog and Northwestern salamander embryo mortality can be predicted from concentrations or levels of select water quality, hydrology and soil parameters.
5. Embryo mortality for both species is most consistently related to conductivity.

Implications for Wetland and Watershed Management

The results of this study suggest that amphibian embryos may be valid candidates for biomonitoring of wetland water quality, hydrology and soil characteristics. Using amphibians as bioindicators can save time and money when integrated with standard monitoring techniques. Further research is recommended to confirm and expand upon these findings. In terms of the health of the specific amphibian species studied herein, the findings presented here could lead to best management practices to control pollutants accounting for increases in the following parameters in wetlands: conductivity, water level fluctuation, total petroleum hydrocarbon, total suspended solids, turbidity, total phosphorus, ammonia, heavy metals in soils (arsenic, cadmium, copper, lead and zinc), and decreases in the following parameters: magnesium, calcium, and dissolved oxygen. This study, a second paper published in these proceedings (Azous and Richter) and a companion study (Richter and Roughgarden, in prep.; Platin, 1994) find a strong basis for the stabilization of water level fluctuations created by urbanization within a wetland's watershed.

ACKNOWLEDGMENTS

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GUIDELINES FOR MANAGING URBAN WETLANDS

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

ABSTRACT

From its inception the Puget Sound Wetlands and Stormwater Management Research Program has focused on deriving a foundation for managing both wetlands and urban stormwater in concert for optimum resource protection. Beginning with the first extensive field data collection, emphasis was placed on interpreting findings for this purpose. The resulting recommendations were put in a systematic, stepwise framework to guide a user through an analysis of a specific case. An "adaptive management" approach was taken, in which guidelines were stated on the basis of the best information available and altered whenever new information warranted. This process will continue until all data are analyzed at the program's conclusion, when the preliminary guidelines will be finalized.

The management guidelines are organized as a series of interconnecting guide sheets. The structure of each guide sheet and the overall set is a branching decision tree, in which, depending on the problem being considered and its nature, the user is directed to the needed guide sheet(s) and the provisions pertaining to the situation. The guidelines overall emphasize managing wetlands in the context of the larger landscape of which they are a part and taking preventive actions at the potential sources of aquatic ecosystem impacts. Key specific guidelines include provisions to regulate hydrologic change resulting from stormwater discharge to proteet various kinds of vegetation communities prevalent in Puget Sound basin wetlands and native amphibians that breed in these wetlands.

A number of local governments and the Washington Department of Ecology have applied the preliminary guidelines to aid decision making. King County Surface Water Management Division has made the most use of them thus far, applying them in basin and master drainage planning efforts. It was possible with analyses based on the guidelines to prescribe land use controls and stormwater management strategies that are expected to protect wetland resources in areas experiencing urban development.

GUIDELINE DEVELOPMENT PROCESS

Since its beginning in 1986 the Puget Sound Wetlands and Stormwater Management Research Program has aimed at developing and disseminating recommendations for managing both wetlands and urban stormwater in concert for optimum resource protection. Following initial literature review and field research, the first attempts were made to express the management lessons that could be extracted from the information then available. Titled *Wetlands and Stormwater Management (Preliminary Guidelines)*, the recommendations were put in a systematic, stepwise framework to guide a user through an analysis of a specific case. The guideline development process was cast in an "adaptive management" framework, wherein management advice was advanced on the basis of the best information available, with the clear understanding that this advice would be altered in response to better information. Numerous drafts of the preliminary guidelines have been produced to date as understanding has improved with the arrival of more data. Each draft, including the current one (Puget Sound Wetlands and Stormwater Management Research Program 1994), has been put into use in the absence of any alternative to aid in reaching management decisions that have to be made, with the idea that the experience gained can feed back to improve future versions. This process will continue through the completion of the program in 1996, when the preliminary guidelines will be finalized.

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The preliminary guidelines got their first application with their incorporation in the *Stormwater Management Manual for the Puget Sound Basin* (Washington Department of Ecology 1992). They are serving to aid several local jurisdictions around Puget Sound in making decisions about urban wetlands and stormwater, most extensively in King County. This paper concludes with a case study of their application by King County Surface Water Management Division.

STRUCTURE AND PRINCIPLES OF THE GUIDELINES

The preliminary guidelines are organized as a series of seven interconnecting guide sheets plus five appendices, which provide supplementary information to users. The guide sheets are:

Guide Sheet 1—General Approach and Problem Definition
Guide Sheet 2—General Wetland Protection Guidelines
Guide Sheet 3—Runoff Quantity Control Guidelines
Guide Sheet 4—Runoff Quality Control Guidelines
Guide Sheet 5—Managing Wetlands in a Newly Developing Area
Guide Sheet 6—Wetland Site Selection Criteria
Guide Sheet 7—Monitoring Guidelines

Making up the appendices are:

Appendix A—Information Needed to Apply Guidelines
Appendix B—Definitions
Appendix C—References
Appendix D—Native and Recommended Noninvasive Plant Species for Wetlands in the Puget Sound Region
Appendix E—Common Stormwater Management Procedures

The structure of each guide sheet and the overall set is a branching decision tree, in which depending on the problem being considered and its nature, the user is directed to the needed guide sheet(s) and the provisions pertaining to the situation. Figure 1 diagrams the guidelines and the relationships among the parts. A fundamental management principle underlying the guidelines is a problem-solving approach to management decision making. The hallmarks of this approach are, first, clearly defining a problem in terms of water quantity or quality control in an area of existing development or managing wetlands in a newly developing area, and then performing a comprehensive analysis of alternative solutions to the problem with the goal of achieving optimum resource protection in the landscape unit. A user implements this approach by stating the management problem to be analyzed clearly, selecting a guide sheet representing that problem, and then following the instructions and answering the questions in that guide sheet and others referenced. It may be seen in Figure 1 that Guide Sheet 2 (Wetland Protection Guidelines) is central to any analysis, being brought into play at the appropriate point in each problem analysis to assess the implications of possible management actions for wetland ecosystems and specify limits and protective strategies.

It is apparent from examining Figure 1 that the guidelines are somewhat complex, especially if an involved problem or a set of problems is analyzed. While it is feasible to use them in a printed form, a more convenient computerized version is also being developed. Using the HyperCard software package, an earlier version of the preliminary guidelines was programmed for interactive access on both IBM-compatible and Apple Macintosh personal computers. The interactive version leads a user from point to point depending on answers given without requiring reference to material extraneous to the problem.

In addition to the problem-solving approach described, the guidelines embrace other fundamental principles. For one, wetland management is framed according to a holistic concept, in which wetlands are regarded as part of a system in a larger landscape. This view has a number of implications for how they are managed, such as: (1) it is necessary to consider incidental effects on wetlands of activities in their watersheds, along with any engineering performed on the wetland itself for stormwater management

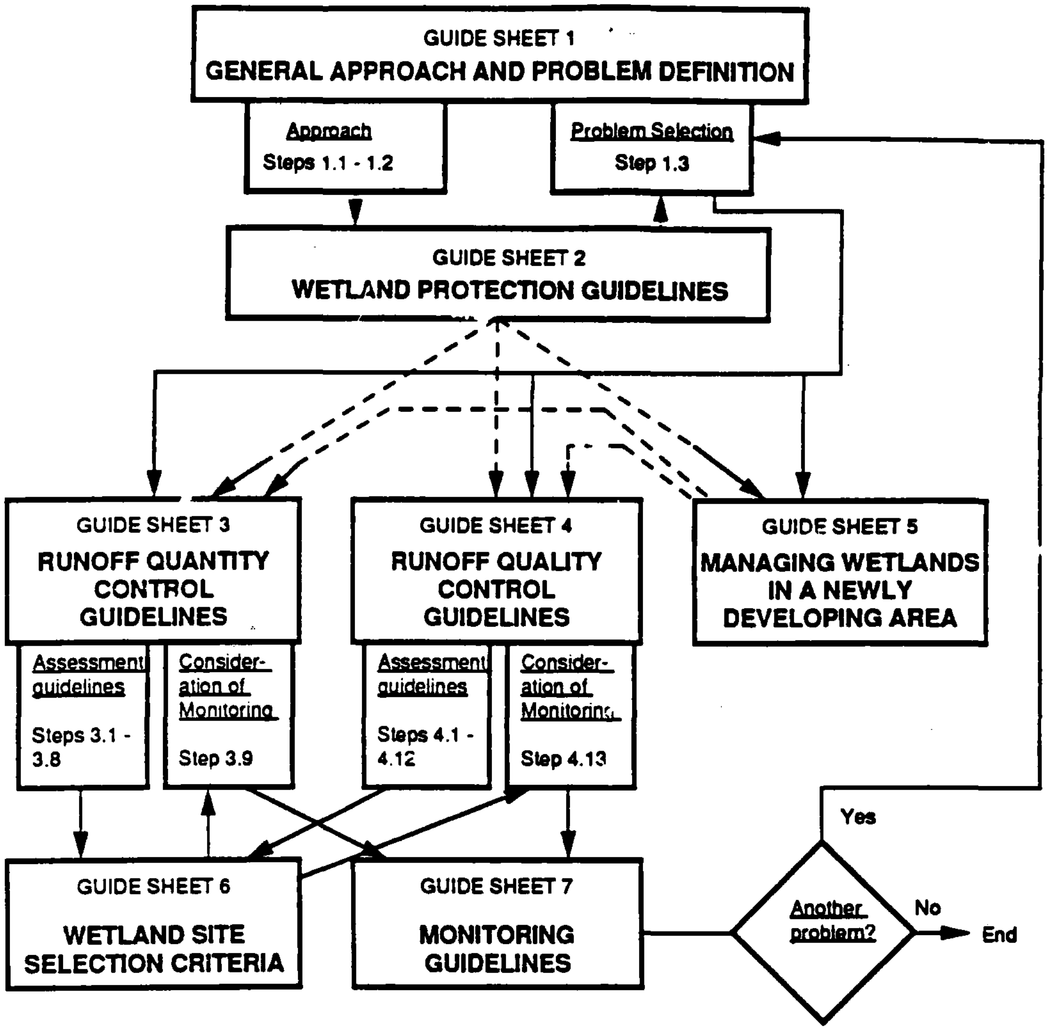

Figure 1. Organization of the preliminary Wetlands and Stormwater Management Guidelines

purposes; (2) wetland responses and how they should be managed depend on a host of landscape factors, including retention of forest and other natural cover, maintenance of natural storage reservoirs and drainage corridors; the separation of human activities from wetlands; and public awareness. Another principle underlying the guidelines is heavy emphasis on source control practices that prevent or minimize quantities of runoff and release of pollutants, with downstream retention/detention for quantity control and treatment for pollutant capture regarded as secondary back-up measures where source controls alone can not ensure resource protection.

KEY SPECIFIC GUIDELINES

The problem most frequently encountered in using the guidelines is control of storm runoff quantity for flood prevention, stream channel protection, or both. The problem usually arises as potential modification of a wetland's hydrology incidentally as land use changes in its watershed, but it can be posed by a specific proposal to alter a wetland for stormwater management benefits. The research has also shown that

hydrologic changes can have more immediate and greater effects on the composition of vegetation and amphibian communities than reduced water quality has, at the levels of water quality experienced by wetlands in developing areas around Puget Sound (Taylor, Ludwa, and Horner, 1995; Cooke and Azous, 1995; Azous, 1995; Platin and Richter, 1995).

This observation and the prominence of the issue have led the Puget Sound Wetlands and Stormwater Management Program to give substantial attention to guidelines for regulating wetland hydrology in order to avoid or minimize negative effects on plant and animal species and communities. These guidelines are directly responsive to the original management needs stated for the program of developing allowable runoff storage schedules that avoid or minimize negative effects on wetlands and their various functions and management criteria by wetland type (Horner, 1995). Specifically found in the research to be crucial to biological responses is wetland hydroperiod, which refers to the depth, frequency, duration, and pattern of wetland inundation. A key variable is water level fluctuation (WLF), measured as the difference between maximum depth and average base depth in a time period (Taylor, 1993; Taylor, Ludwa, and Horner, 1995).

Table 1 lists the hydroperiod provisions incorporated in the preliminary guidelines. Applying these guidelines requires specific information on hydroperiod characteristics, which can come only from monitoring at the wetland in question before a management decision has to be made or prediction by a mathematical hydrologic model. These guidelines have been structured to be used with output from the Hydrologic Simulation Program-FORTRAN (HSPF) model, which is quite widely used in the Puget Sound region.

Table 1. Hydrologic guidelines for protection of wetlands that receive urban stormwater discharges

DEPTH LIMITS

All wetlands (all year):

Limit post-development increase in annual maximum depth to 30 cm (for 1.01 to 100 year frequency rainfall events).

Emergent and scrub-shrub wetlands and zones (all year):

Limit post-development average monthly WLF (for each month in the year) to: (1) an increase of 5 cm if pre-development WLF is greater than or equal to 15 cm; or (2) a maximum of 20 cm if pre-development WLF is less than 15 cm.

FREQUENCY AND DURATION LIMITS

Note: These guidelines envision a fluctuating stage over time before development that could fluctuate more, both higher and lower, after development; these greater fluctuations are called "excursions." The guidelines set limits on the amount of the excursions and the total time, over one or more episodes, that they can occur in a given period.

Wetlands with breeding native amphibians, 1 February-31 May:

Limit the magnitude of post-development stage excursions above or below the pre-development stage to no more than 8 cm, and limit the duration of these excursions to no more than 24 hours in any 30 day period.

All wetlands (1 February-30 September):

Limit the magnitude of post-development stage excursions above or below the pre-development stage to no more than 30 cm for any length of time.

Limit post-development stage excursions of 15-30 cm above or below the pre-development stage to a total duration of no more than 72 hours in any 30 day period.

Table 1 continued

Limit post-development increase or decrease in dry period (when pools dry down to the soil surface everywhere in the wetland) to two weeks in any year in wetlands with pre-development dry periods averaging greater than eight weeks.

Limit post-development dry period to a total of 10 weeks in any year in wetlands with pre-development dry periods averaging less than eight weeks.

Peat wetlands (bogs and fens as more specifically defined by the Washington Department of Ecology):

Limit post-development stage excursions above the pre-development stage to a total duration of 24 hours in any year.

Forested wetlands and zones (wetlands or zones with at least 30% cover of trees at least 20 feet tall):

Limit the magnitude of post-development stage excursions above the pre-development stage to no more than 20 cm, and limit the duration of these excursions to no more than 48 hours in any seven-day period during the early growing season (1 March-31 May) and to 96 hours total over the full growing season (1 March-31 August).

Avoid sediment accumulation of more than 20 cm in any year.

Sedge meadows (wetlands or zones with at least 20% cover by *Carex, Eleocharis, Scirpus,* or *Dilichium*):

Avoid sediment accumulation of more than 15 cm in any year.

APPLICATION OF WETLAND GUIDELINES IN KING COUNTY

The data and information compiled by the Wetlands Research Program and selected management guidelines have been applied in King County in both the basin and master drainage planning processes. Most of the applications have focused on water level fluctuation, since this has the most direct effect on wetland functioning, vegetation communities, and habitat (particularly for breeding amphibians). Regulations governing factors that affect WLF have been targeted at new development on the urban side of the Urban Growth Boundary (UGB), where the most significant impacts are likely to occur. The general information on construction impacts generated by the Wetlands Research Program has also led to the application of seasonal clearing limits in the drainage areas of Class 1 wetlands.

Basin Planning and Wetland Management Areas

The basin planning process was developed by King County to address the significant and rapid land use changes occurring in the county that have an impact on water resources, including flooding, habitat, and water quality. The outcome of the basin planning process is a comprehensive set of management recommendations that involve development regulations, capital improvement projects, education programs, improved maintenance practices, and monitoring.

The East Lake Sammamish Basin Plan (King County Surface Water Management Division (KCSWM) 1992) is an example where the results of the Wetlands Research Program were directly applied to management solutions. The East Lake Sammamish basin encompasses about 16 square miles east of Lake Sammamish. Since 1980, the basin has experienced rapid development, converting from low-density residential and forested land uses to higher-density residential and some commercial uses. The diversity of the basin's more than 40 inventoried wetlands is as great as anywhere in King County, with nine wetlands ranked as unique and outstanding (Class 1 rating). As one of the prime resources in the basin, wetlands received significant attention for protection from the county and the citizenry.

Before adoption of the basin plan, wetland protection in King County was achieved primarily through the Sensitive Areas Ordinance (SAO). The wetland protection in the SAO provides for discrete buffer widths as a function of assigned rating (e.g., 100 feet for Class 1 wetlands). Although these buffers confer some protection on various wetland elements, they ignore other functional wetland characteristics such as WLF influenced by the broader watershed and surrounding landscape. To address these issues, King County developed wetland management areas (WMA) focused on watershed-based controls to protect the nine Class 1 wetlands. The intent of these controls was to minimize the stormwater-related impacts on wetlands by minimizing impervious surfaces, retaining forests, clustering, and providing constructed infiltration systems, where feasible.

A major component of the wetland management strategy was the limitation of total impervious area in the catchment to 8 percent, where allowed by zoning. From the Wetlands Research Program data, it was clear that there were significant increases in WLF between wetlands with watersheds less than 4 percent impervious surface and those with watersheds greater than 12 percent impervious surface (Taylor, 1993; Taylor, Ludwa, and Horner, 1995). It was difficult to define this more precisely because of the absence of impervious surfaces between 4 percent and 12 percent. Booth and Reinelt (1994) summarized several data sets showing loss of aquatic system function with impervious surface areas above about 10 percent, as measured by changes in channel morphology, fish and amphibian populations, habitat, and water chemistry. While the precise threshold will vary by watershed and the effectiveness of mitigation strategies, 8 percent to 10 percent impervious surface appears to be an appropriate threshold.

A requirement for 50 percent forest retention was also imposed in the catchments of some wetlands. This limitation is consistent with King County's reserve tract requirements associated with clustering and growth-reserve zoning. Taylor (1993) found a correlation between forest retention and reduced WLF, but no specific threshold was identified in this work. Clustering of development away from hydrologic source areas (landscape features transmitting water to wetlands during the wet season) was also recommended. An additional requirement in one wetland watershed was the use of constructed infiltration systems to reduce increases in stormwater volumes. This was feasible given the extensive glacial outwash soils in this watershed that were amenable to substantial infiltration. Finally, seasonal clearing limits for construction activities were imposed in eight of the nine watersheds. This limitation prevents clearing and grading during the wet season (October-April), when up to 88 percent of erosion occurs (KCSWM, 1992).

King County has continued this approach of wetland management areas for protection of Class 1 wetlands in the Cedar River Basin Plan currently under development. Four Class 1 wetlands in the Cedar basin that are on the urban side of the UGB or that receive runoff from urban areas have been targeted.

Master Drainage Planning and Guidelines

King County uses the Master Drainage Planning (MDP) process for large or complex development sites to assess the potential impacts of development on aquatic resources (KCSWM, 1993). The MDP process is required for Urban Plan Developments (UPD), for subdivisions with more than 100 single-family residences, and for projects that clear 500 acres or more within a subbasin. In addition, there are lower thresholds for development in the drainage areas of Class 1 wetlands, in regionally significant resource streams, or over sole source aquifers. For Class 1 wetlands, an MDP is required if a project seeks to convert more than 10 percent of the wetland's total watershed area to impervious surface.

The updated guidelines for MDP monitoring and studies (KCSWM, 1993), supported in part by results of the Wetlands Research Program, require monitoring for purposes of: (1) assessing wetland functions in storing and releasing stormwater, (2) determining baseline WLF in relation to vegetation and amphibian communities, and (3) establishing baseline conditions from which to measure potential post-development changes. Specific concerns potentially resulting from development are: (1) loss of live storage and infiltration functions of wetlands, (2) stability of outlet control conditions, (3) the effects of increases in flow rates and volumes, (4) changes in spring WLF and resultant habitat changes, and (5) changes in groundwater and interflow.

For purposes of assessing wetland impacts, the MDP guidelines require determination of the following: bathymetry (morphometry) of the wetland; outlet control description and measurement; stage-discharge volume relationships; surface area of open water, including ordinary high water levels; and the dead and live storage maximum elevation and volume. Specific monitoring requirements are: (1) monthly instantaneous and crest water levels to determine WLF in the permanent pool area of the wetland; (2) inflow and outflow rates of the wetland; and (3) the duration of summer drying, if applicable.

North Fork Issaquah Creek Wetland 7 Management Area and Grand Ridge MDP

The East Sammamish Community Plan limited development in the drainage area tributary to North Fork Issaquah Creek Wetland 7 (NFIC-7), a Class 1 wetland, to no more than 8 percent impervious surfaces and 65 percent forest retention. This condition applies to all development proposals submitted prior to adoption of the Issaquah Basin Plan (KCSWM, 1994) and for all developments not going through the MDP process. In the basin plan, impervious surfaces are limited to a maximum of eight percent for all new subdivisions, short subdivision, and UPDs.

The proposed Grand Ridge development in the North and East Fork Issaquah Creek basins involves two development options: rural estates at a density of one unit per 5 acres and an urban proposal consisting of 580 acres of urban development and 1400 acres of permanent open space. In a study of potential development scenarios carried out using the Wetlands Research Program guidelines and a model developed by Taylor (1993), it was possible to examine the development impacts on the water level fluctuation of wetland NFIC-7. The Taylor model involves a multiple regression to estimate mean WLF based on impervious surface coverage, forested coverage, and outlet constriction. The model uses either a continuous (percent) or categorical (0 if <20% or 1 if >20%) variable for impervious surface, a continuous variable for forested coverage and a categorical variable for outlet constriction (1 for relatively restricted or 0 for unconstricted).

Using the Taylor model, it was possible to show that the rural estates proposal (with approximately 4 percent impervious surface and 65 percent forest retention) could maintain WLF within the research program's preliminary guidelines (limiting mean WLF increase after development to 5 cm in wetlands that have pre-development mean WLF > 15 cm). An analysis of full buildout under urban densities with 18 percent impervious surfaces and 20 percent forest retention showed WLF increases of 10-17 cm, depending on which form of the model was used. This WLF increase can be reduced substantially through mitigations that focus on maintaining greater forested area and using infiltration to reduce stormwater volumes. Under the current proposal of 12 percent impervious surface and 75 percent forest retention, the models estimate a 1-7 cm increase. When combined with the use of on-site infiltration (dispersed roof runoff and road runoff after pre-treatment), stormwater volume and wetland WLF changes will be further reduced. Unfortunately, the effectiveness of infiltration cannot be modeled using the Taylor model.

CONCLUSIONS

The application of the preliminary guidelines to King County's basin planning and master drainage planning efforts have been a good test case of their efficacy. Controls focused on minimizing impervious surfaces and maximizing forest retention are likely to be the most widely usable effective strategies; however, additional mitigations that reduce stormwater volumes through infiltration can also be used when hydrogeological conditions permit. The Taylor model is a useful tool for examining development proposals with alternative coverages of impervious surface and forest; however, it is not possible to examine the benefits of infiltration in reducing wetland WLF.

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PUGET SOUND RESEARCH '95

SESSION 2A

FUNCTION, VALUE & PRESERVATION OF FISH HABITAT

Session Chair:

Jim West
Washington Department of Fish & Wildlife

IDENTIFICATION AND PROTECTION OF NURSERY HABITATS FOR JUVENILE ROCKFISH IN PUGET SOUND, WASHINGTON

Daniel C. Doty, Raymond M. Buckley and James E. West[1]

INTRODUCTION

The protection of habitats that support natural production of marine fish resources is a critical component in managing and maintaining a healthy ecosystem in Puget Sound. Nearshore estuarine wetland habitats, primarily vegetated intertidal and shallow subtidal habitats, are particularly vulnerable to destruction and degradation by human activities. These habitats are critical feeding and nursery areas for a number of marine fish species important for commercial and recreational fisheries, and they support critical links in the marine food web for the estuarine ecosystem (Levings and Thom, 1994; B.C./WA. Marine Science Panel, 1994). Substantial amounts of nearshore habitat have been lost in Puget Sound, and a variety of human activities (e.g., dredging and filling, bulkheading, oil spills, construction and siltation) continue to threaten the quality and quantity of remaining marine habitats.

Copper *(Sebastes caurinus)*, quillback (*S. maliger*) and brown (*S. auriculatus*) rockfish are among the most popular and important of the marine fish species caught by recreational anglers in natural and artificial reefs in Puget Sound (Palsson, 1988). Older juveniles and adults of these three species are commonly observed in natural and artificial rocky reefs in the region. Young-of-the-year (YOY) juveniles are not abundant in areas with sub-adults and adults (personal observation), suggesting that settlement and initial rearing occur in other habitats. The information available on natural habitats suggests that YOY rockfish settle initially into shallow, vegetated habitats of bull kelp (*Nereocystis luetkeana*), macroalgae, and eelgrass (*Zostera marina*) in the region (Miller et al., 1976; Miller et al., 1978; Phillips, 1984; Stober and Chew, 1984; Haldorson and Richards, 1986; Matthews, 1990; Norris, 1991). There is evidence that YOY segregate themselves from adults by depth and substrate type on artificial reefs (West et al., 1994). At the present time, however, there is little information on specific locations where settlement and initial rearing occurs in Puget Sound, or on whether there are areas that may be particularly valuable as nursery areas for maintaining natural production.

The objectives of this study were: 1) to identify settlement and nursery habitats of post-larval, young-of-the-year copper, quillback and brown rockfish in Puget Sound; and 2) to obtain information on the specific functions of these habitats in the life cycles of these species. This information included identifying where settlement occurred, which habitats were used as nursery habitats, and when fish settled and used these areas.

METHODS AND MATERIALS

Spatial Distribution of YOY Rockfish in Puget Sound Habitats

We surveyed kelp, eelgrass and macroalgae habitats at a variety of locations in Puget Sound during 1991 and 1992 to examine the geographic distribution of settlement. Surveys were conducted throughout the year, but the major effort was between July and December to focus on the suspected period of peak settlement. Pilot surveys in 1990 suggested that YOY rockfish settled into nearshore habitats between August and November. We surveyed 33 locations in the main basin of Puget Sound during these months to examine spatial distribution of YOY rockfish at various sites and habitats.

All surveys were conducted by diver-pairs using scuba. Dives were typically 30-60 minutes long and involved a thorough search of the area. Two types of surveys were used: Qualitative searches were used to find YOY rockfish, and quantitative surveys were used to estimate YOY abundance. For qualitative surveys, we searched the dominant habitats and noted the presence or absence of YOY rockfish in each.

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At all locations we classified the substrate type based on a modified version of the habitat classification system of Dethier (1990). Divers noted which habitats fish were using when observed. We grouped these observations into four general habitat categories: (1) bull kelp/macroalgae (KM), which consisted of bull kelp beds with an associated understory of brown algae (primarily *Laminaria saccharina, Costaria costata,* or *Agarum fimbricatum*), red algae (i.e., *Gigartina exasperata*) and green ulvoids (*Ulva* spp.); (2) macroalgae (MA), which consisted of brown algae, red algae and green ulvoids without bull kelp; (3) eelgrass beds (EG); or (4) unvegetated (UV) substrate without macrophytes.

When YOY and juvenile rockfish were observed, quantitative strip transects were conducted to estimate YOY rockfish density within the dominant habitat(s) at each location. Three to five transects were made in each habitat. The starting point of the initial transect was selected randomly within the specific habitat. Subsequent transects were made parallel to the first and spaced 20 meters to 50 meters apart. For each transect a diver swam along each side of a transect tape, counting YOY, estimating the size and noting the habitat type, within 1.5 meters to 2 meters of the line. Species were identified (when possible), and the total length (TL) of the fish was estimated visually. We collected fish using hand nets at several locations during July-October. These fish were identified and measured to the nearest mm (TL) to determine size distribution and to assess our ability to estimate fish sizes visually underwater. Transects were typically 30-100 meters in length. If habitats (KM, EG, MA, UV) changed along the transect, the habitat type and the distance along the transect were noted. YOY density was then calculated by habitat category.

Temporal Patterns of Density and Distribution of YOY Rockfish by Habitat

In addition to our surveys of other locations, we surveyed one location north of Carkeek Park in Seattle (Figure 1) at several different times from 1991-1993 (October 1991, December 1991, July 1992, September 1992, October 1992, May 1993 and August 1993) to examine temporal changes in density and to compare densities among habitats. Patches of KM, EG, MA and UV habitats were interspersed throughout area at this site, and we estimated rockfish density in each habitat at this location. Densities among habitats were compared using non-parametric tests (Mann-Whitney or Kruskal-Wallis ANOVA).

RESULTS

Spatial Distribution of YOY Rockfish in Puget Sound Habitats

YOY rockfish were found in vegetated habitats at 16 of the 33 locations surveyed in Puget Sound during August-November in 1991 and 1992 (Table 1). YOY rockfish were most commonly found in kelp beds (KM habitat) and were observed at 14 of the 25 locations with this habitat. YOY rockfish were present at 19 percent of the locations with EG and 15 percent of the sites with MA habitat. No YOY fish were observed in UV habitat at any of the survey locations.

In 1991 and 1992, settlement appeared to be concentrated primarily along the eastern shoreline of Puget Sound and north of Elliott Bay in Seattle (Figure 1, Table 1). YOY rockfish were present at nearly all the KM and EG habitats surveyed in this area. In contrast, YOY rockfish were found at only one of nine KM beds and at none of the five EG beds surveyed south of Elliott Bay and along the western shoreline of central Puget Sound (CPS). The KM beds where we documented rockfish settlement in Puget Sound were typically attached to "mixed-coarse" or "cobble" substrate with a few scattered boulders in the intertidal and shallow subtidal region at depths shallower than 15 m mean lower low water (MLLW). EG was typically found on shallow intertidal and subtidal sand substrate (at depths shallower than 15 m MLLW).

Table 1. Locations and habitats surveyed in central Puget Sound during the August-November period of rockfish settlement in 1991 and 1992 (KM = bull kelp and macroalgae; MA = macroalgae without bull kelp; and EG = eelgrass). The presence (+) or absence (o) of young-of-the-year rockfish is indicated (ns = habitat not present in survey area). Refer to Figure 1 for map of survey locations.

		Habitat		
No.	Survey Location	EG	MA	KM
1	Whidbey Island- Double Bluff	o	o	+
2	Foulweather Bluff	o	o	o
3	Cultus Bay/Scatchet Head	o	o	o
4	Camano Head	ns	o	+
5	Gedney Island	ns	o	+
6	Picnic Point - south	+	ns	ns
7	Norma Beach - north	o	ns	ns
8	Meadowdale - Browns Bay	+	ns	+
9	Edmonds	ns	o	+
10	Edmonds Breakwater	ns	ns	+
11	Edwards Point	o	+	ns
12	Point Wells–north	o	ns	+
13	Boeing Creek	o	+	+
14	Spring Beach	+	ns	ns
15	Carkeek Park	+	+	+
16	Port Madison - East of Indianola	o	o	ns
17	Port Madison - Suquamish	o	o	ns
18	Shilshole Jetty	ns	ns	+
19	West Point - Shilshole Bay	o	+	+
20	West Point - Discovery Park	o	o	+
21	Magnolia Bluff	o	o	+
22	Magnolia Marina Breakwater	ns	o	o
23	Point Williams - Lincoln Park N.	o	o	o
24	Point Williams - Lincoln Park S.	o	o	o
25	Blakely Rocks	ns	o	o
26	Blakely Point	ns	o	ns
27	Blake Island - west	ns	o	o
28	Blake Island - south	o	o	o
29	Orchard Rocks	ns	o	o
30	Point White	ns	o	o
31	Vashon Island - Aquarium	o	o	ns
32	Maury Island - Maury	o	o	+
33	Day Island	ns	o	o

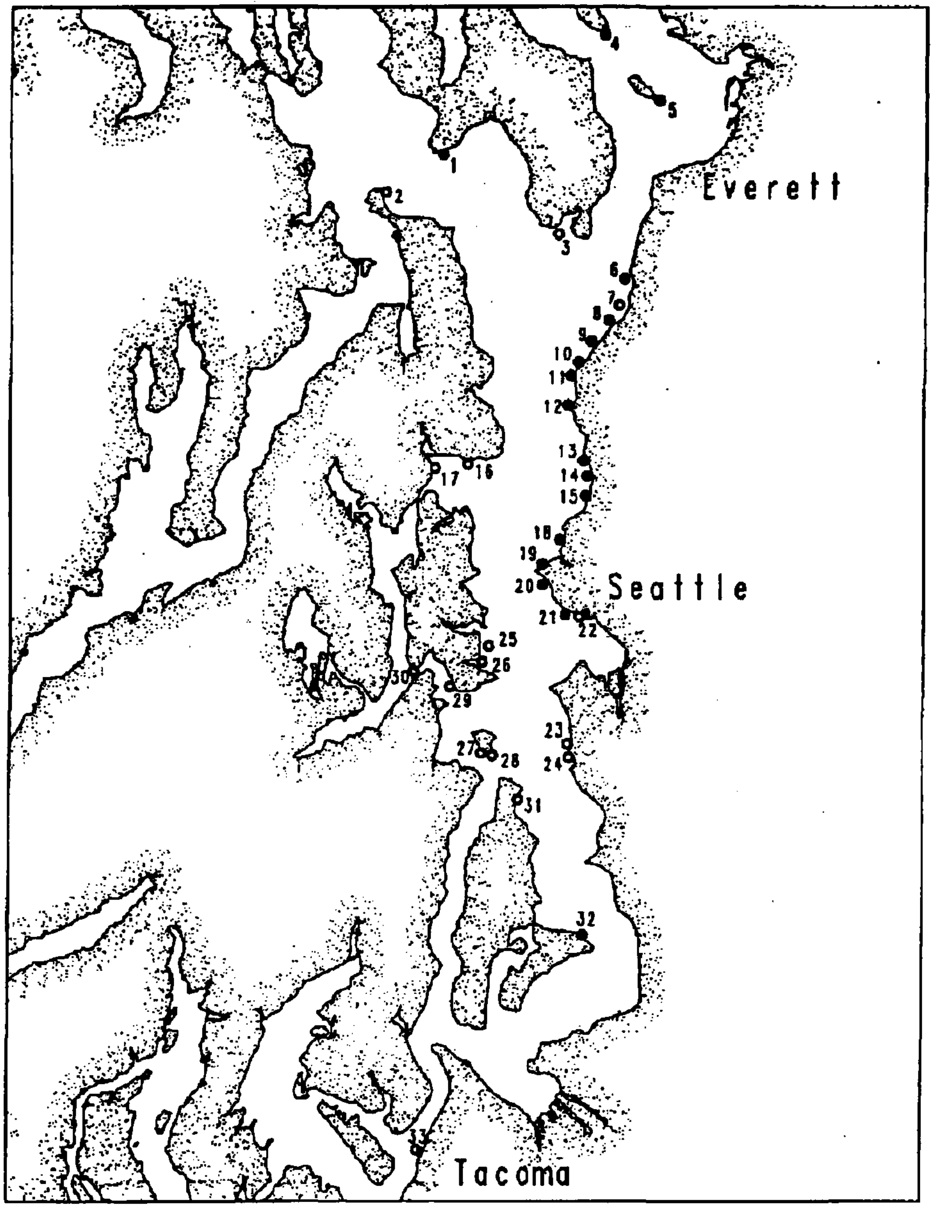

Figure 1. Map of survey locations in the main basin of Puget Sound. Surveys were conducted during the August-November period of rockfish settlement in 1991 and 1992. Locations denoted with a dot (●) indicate that young-of-the-year rockfish were found in one or more vegetated habitats in the area. Locations with an open circle (O) denote areas where no young-of-the-year rockfish were found. Refer to Table 1 for the name of each survey location, what habitats were surveyed, and which habitats had young-of-the-year rockfish.

Temporal Patterns of Density and Distribution of YOY Rockfish by Habitat

Newly settled rockfish were first observed in KM and EG habitats in mid-July 1991. In July, the size of fish ranged from 21 to 37 mm TL and averaged 27 mm TL (± 1 mm SE, n=28; Table 2). Average total length increased in subsequent months and by October was 45 mm TL (± 1.4 mm SE, n=135; range 19-80 TL mm). Small rockfish (19-21 mm TL) were present in samples during all four months, suggesting that settlement continued at least through October.

Table 2. Average total length (mm), standard error (SE), sample size (n), and size range (minimum and maximum) of YOY rockfish collected from KM, EG and MA habitats in Puget Sound in 1991

Month	n	Avg TL (mm)	SE	Min. size (mm)	Max. Size (mm)
July	28	27.3	0.9	21	37
August	42	31.1	0.8	23	45
September	84	43.5	1.3	20	75
October	135	45.0	1.4	19	92

YOY rockfish were present in KM, EG and MA habitats from July to December 1991 and 1992. Average density data from all survey sites were combined to illustrate temporal patterns of abundance of YOY copper, quillback and brown rockfish in Puget Sound KM habitat during 1992 (Figure 2; abundance in MA and EG is not included because we did not consistently find or quantify fish in these habitats). Abundance increased in September, peaked in October and then declined in November and December. Very few YOY rockfish were observed in shallow water habitats at any location between December and July.

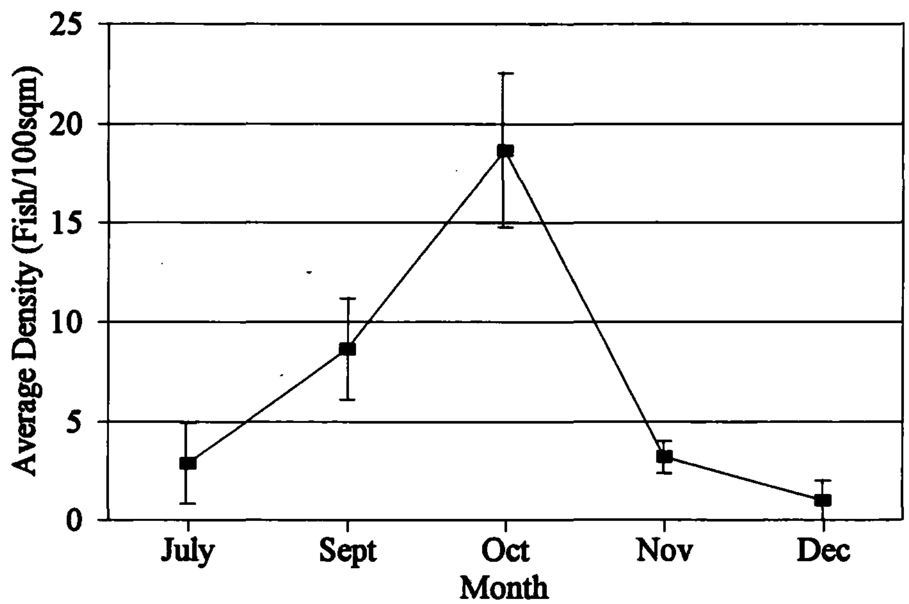

Figure 2. Average density (± 1 SE) of young-of-the-year copper, quillback and brown rockfish in kelp/macroalgae (KM) habitat in Puget Sound by month in 1992

YOY rockfish were always observed in association with some type of vegetation. YOY rockfish were most commonly found in bull kelp beds (KM) and were observed hiding in the canopy near the surface, next to stipes, and associated with macroalgae in the understory. In MA habitat, fish were observed hiding in the folds of plants. In EG habitat, fish were observed hovering among the blades of eelgrass, particularly along the edges of beds and in smaller patches of eelgrass.

YOY abundance differed between habitats. In general, YOY rockfish were found in highest densities in KM habitat, followed by MA and EG. At the Carkeek Park site on 14 October 1991, mean densities (± 1 SE) of YOY rockfish were 24.0 (± 2.2), 6.3 (± 3.4), 0.7 (± 0.7) and 0 fish/100m^2 in KM, MA, EG, and UV, respectively (Figure 3). Density was significantly higher in KM habitat than in adjacent MA, EG and UV habitats (p=0.001; Kruskal-Wallis ANOVA). Subsequent surveys at the Carkeek Park site indicated that KM habitat consistently supported higher densities of YOY rockfish than did EG habitat in the same area (Figure 4). In 1992, KM habitat supported higher rockfish densities than did EG during all three months surveyed, although densities were significantly higher in the KM habitat only during September (p=0.009; Kruskal-Wallis ANOVA).

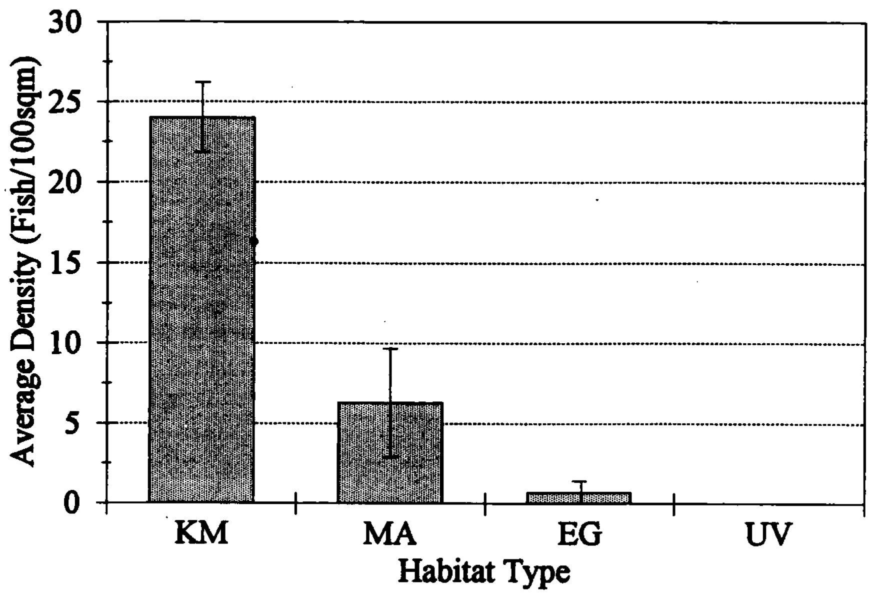

Figure 3. Average density (± 1 SE) of young-of-the-year copper, quillback and brown rockfish in each of four different habitat types (KM = bull kelp/macroalgae; MA = macroalgae without bull kelp; EG = eelgrass; and UV = unvegetated substrate) at Carkeek Park location in October 1991

Densities of YOY rockfish in KM habitat at the Carkeek Park site differed substantially between 1991 and 1992. In October 1991 the average density YOY rockfish in KM habitat was 24 fish/100m^2. In contrast, YOY density in KM habitat was less than 2 fish/100m^2 in October 1992 (Figure 4).

Densities of YOY rockfish varied between locations and habitats but were typically higher in KM beds than in EG beds. Average densities (± 1 SE) of YOY rockfish along the eastern shoreline of Puget Sound during late September and early October 1992 were 18.4 (± 6.5) fish/100 m^2 in KM habitat (n=4 locations) and 3.4 (± 1.6) fish/100 m^2 in EG habitat (n=5 locations).

YOY rockfish abundance declined dramatically at all sites after October and by December fish were rarely observed in shallow habitats. It appears that most YOY rockfish left shallow habitats by December. No YOY rockfish were found in the KM, MA or EG habitats during surveys at Carkeek Park on 4 December 1991 (Figure 4). This was typical of what we found at other sites in 1991 and 1992.

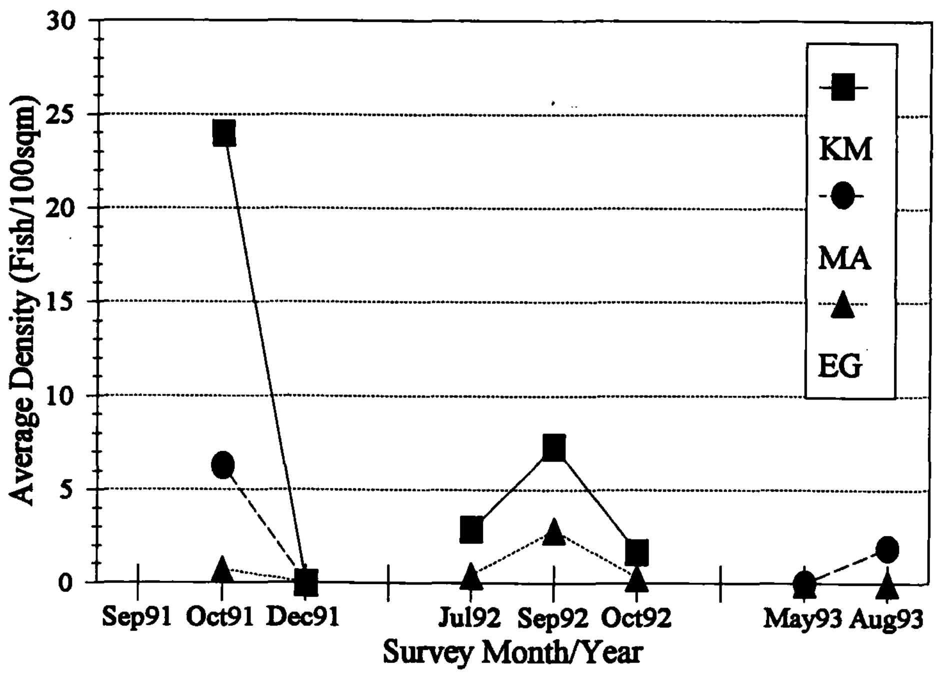

Figure 4. Average density of young-of-the-year copper, quillback and brown rockfish in each habitat type (KM = bull kelp/macroalgae; MA = macroalgae without bull kelp; EG = eelgrass) surveyed at the Carkeek Park location between October 1991 and August 1993

DISCUSSION

Spatial Distribution of YOY Rockfish in Puget Sound Habitats

In 1991 and 1992, settlement and initial rearing of YOY rockfish appeared to be concentrated primarily along the northeastern shoreline of central Puget Sound (CPS) north of Seattle, suggesting that there was a strong spatial component controlling settlement. We documented YOY rockfish in bull kelp and eelgrass beds along this section of shoreline. In contrast, many of the kelp and eelgrass beds that we surveyed in other areas of Puget Sound appeared structurally similar to sites that contained YOY rockfish, yet no YOY rockfish were observed.

The presence of fish at nearly all survey locations in the northeastern region of CPS may indicate that a high proportion of pelagic larvae and juveniles were present in this area during the settlement period. Hydrographic features such as prevailing tidal currents and localized eddies are believed to enhance larval retention in some areas (Moser and Boehlert, 1991). Such mechanisms may influence the distribution and abundance of larval (pelagic) rockfish in Puget Sound and may account for the disparate patterns of settlement that we observed between the east and west side of CPS in 1991 and 1992.

The apparent lack of YOY rockfish recruitment on the western side of CPS during 1991 and 1992 does not mean that these areas are unimportant for YOY rockfish. YOY rockfish have been documented previously at several of the locations on the west side of CPS where we did not find fish (e.g., Stober and Chew, 1984; and Matthews, 1990), suggesting that the distribution of rockfish recruitment in Puget Sound varies from year to year. Rockfish populations are characterized by high interannual variability in the distribution and magnitude of recruitment (e.g., Love et al., 1991; Moser and Boehlert, 1991).

Temporal Patterns of Density and Distribution of Fish by Habitat

Our observations reinforce previous information suggesting that shallow vegetated habitats of KM, MA and EG are temporally important for settlement and initial rearing of copper, quillback and brown rockfish

in Puget Sound (Miller et al., 1976; Miller et al., 1978; Phillips, 1984; Stober and Chew, 1984; Haldorson and Richards, 1986; Matthews, 1990; Norris, 1991). Surveys at the Carkeek Park site and at other locations indicate that fish settled into KM, EG and MA habitats beginning in July and resided in these habitats for up to several months. Newly settled rockfish were always associated with some type of vegetation. Recruitment of a number of rockfish species, including copper rockfish, has been positively correlated with the occurrence of macrophytes (e.g., Carr, 1991; Love et al., 1991).

The recruitment of YOY rockfish in Puget Sound habitats was both spatially and temporally variable. Variability in the recruitment and densities of rockfish may be due to the distribution of pelagic larvae and juveniles and on habitat availability and abundance. At Carkeek Park, variations in YOY rockfish density in KM habitat between 1991 and 1992 appeared to correspond with the changes in the amount of KM habitat at the site. Although we did not quantify changes in habitat at the Carkeek Park site, the site changed dramatically during the study. In September and October 1991, when YOY rockfish densities were the highest, the kelp bed was large and dense, with a lush canopy and thick layer of macroalgae in the understory. In 1992, the kelp bed at the site was substantially smaller, patchier and less dense, and YOY rockfish densities were much lower than the previous year. In 1993, there was virtually no bull kelp or macroalgae present, and few rockfish were observed in the area.

Juvenile rockfish grew rapidly while in shallow vegetated habitats, suggesting that these habitats functioned both as refuge and feeding habitat. Preliminary evidence from trophic studies, conducted at some sites concurrently with this study, suggest that smaller, newly settled YOY rockfish initially fed on planktonic organisms and then switched to epibenthic prey organisms typically associated with macrophytes (Washington Department of Fish and Wildlife, unpublished).

Of the three vegetated habitat types we studied, KM habitats were the most important in terms of relative abundance, supporting consistently higher densities of YOY rockfish during the settlement period at more locations in Puget Sound than did EG or MA habitats. On a smaller spatial scale, KM habitat at the Carkeek Park site supported higher densities of YOY rockfish than other habitat types present in the area, suggesting that KM habitat was the preferred habitat. We do not know whether structural features of the KM habitat complex caused differential recruitment to this habitat or whether differences in abundance among habitats were due to other factors (such as predation).

Our observations of Puget Sound kelp beds suggest that YOY rockfish recruited initially to the kelp canopy and then migrated down into the macroalgal understory, where they spent most of their time before migrating to deeper water habitats. This pattern of habitat use in kelp beds has been documented for copper rockfish and a number of other rockfish species (e.g., Haldorson and Richards, 1987; Carr, 1991; Love et al., 1991).

The disappearance of YOY rockfish during late November and December corresponded with natural seasonal declines in the abundance of the kelp and macrophytes in shallow subtidal areas. In the absence of bull kelp and macroalgae, there were few places to hide in low-relief "mixed-coarse" and "cobble" substrates found at many of the locations. Our observations at the Carkeek Park site and other locations indicate that a few fish may have remained on site, hidden in the boulder and cobble substrate, and re-emerged in the spring. Some juvenile rockfish were observed at the Carkeek Park site in early July 1992. These fish were about 95-105 mm TL and were probably fish from the 1991 cohort. These fish had either remained in the boulder/cobble substrate over the winter or had moved back into the area from other habitats. We do not believe that many fish stayed in these areas through the winter because we rarely observed fish in these shallow habitats after the kelp and macroalgae disappeared, despite intensive searches of the substrate.

Declines in YOY rockfish abundance are more likely due to both emigration and mortality. Some of our observations suggest that YOY rockfish moved out of shallow subtidal habitats and into deeper water with mats of macroalgae and eelgrass as they detached and drifted off of sites. On several occasions in November and December 1991 we observed YOY quillback and brown rockfish (60-80 mm TL) hiding in clumps of detached macrophytes (e.g., *Laminaria* and eelgrass) drifting along the bottom in deeper water (–30 to –60 ft MLLW) in an area north of the Carkeek Park kelp bed. As the abundance of YOY fish

declined in shallow KM and EG habitats, we observed fish colonizing small crevices in deeper-water natural reef habitats (this study) and YOY rockfish began colonizing nearby low-relief artificial reefs (West et al., 1994). Holmquist (1994) found that unattached, drifting, benthic macroalgae can be an effective mechanism for transporting fish and other fauna among habitats. Associating with clumps of drifting macroalgae or eelgrass as they detach from shallow intertidal and subtidal substrates may provide refuge for YOY rockfish as they traverse expanses of mud and sand substrate and until they encounter suitable refuge.

SUMMARY AND CONCLUSIONS

In this study we identified nursery habitats for three demersal rockfish species in Puget Sound. Density of YOY copper, quillback and brown rockfish was spatially and temporally variable among habitats and locations. During this study, recruitment appeared to be concentrated along the northeastern shoreline of central Puget Sound. Rockfish were found using all three of the vegetated habitat types, and kelp habitat supported the highest densities of fish.

The areas where we found YOY rockfish appeared to provide a unique combination of physical and biological attributes for settlement and growth of YOY rockfish during the study period. The vegetated habitats in these areas appear to provide refuge for juvenile rockfish as they make the transition from pelagic to benthic habitats and may be necessary for replenishing and maintaining adult populations of copper, quillback and brown rockfish in Puget Sound. More studies are needed to determine specific functions of these habitats, how dependent rockfishes are on the habitats, and whether the abundance of these habitats represent a significant bottleneck (*sensu* Wahle and Steneck, 1991) in the life history of these species. Further work is also needed to evaluate the relative importance of different geographic regions of Puget Sound for natural rockfish production.

The use of vegetated habitats by juvenile rockfish should be a consideration in habitat management and mitigation activities in the region. In this study, most of the areas where we documented recruitment of YOY rockfish were located along the heavily urbanized section of shoreline of central Puget Sound between Seattle and Everett, where threats of habitat degradation and alteration are common. Changes in the amount and type of habitat in these areas, from both natural and human causes, may affect the natural production of copper, quillback and brown rockfish in Puget Sound. Efforts should be made to ensure that these habitats are protected.

Detailed information from each of these YOY rockfish settlement sites has been provided to WDFW habitat managers to help protect and preserve these habitats. Data from this study have been incorporated into Washington Administrative Codes (WACs; WDFW, unpublished) and have been used by WDFW habitat managers for evaluating hydraulic permit applications, for developing oil spill policy, and for developing a database of priority habitats and species.

ACKNOWLEDGMENTS

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ECOLOGY AND HABITAT USE OF JUVENILE ROCKFISHES (*Sebastes* spp.) ASSOCIATED WITH ARTIFICIAL NURSERY HABITATS IN PUGET SOUND, WASHINGTON

James E. West, Raymond M. Buckley, Daniel C. Doty and Betty E. Bookheim[1]

INTRODUCTION

Rockfishes (*Sebastes* spp) are an important component of recreational and commercial fisheries in northeastern Pacific waters (Gunderson and Sample, 1980; Lenarz, 1987; Westrheim, 1987) and inland marine waters of Washington (Pedersen and DiDonato, 1982). *Sebastes* comprise more than 60 species in the eastern Pacific and more than 30 species in the inland marine waters of Washington state (Miller and Borton, 1980; Eschmeyer et al., 1983; Matarese et al., 1989). This genus has been studied extensively in terms of its adult ecology, taxonomy, life history, and fishery value (see Leet and Reilly, 1988).

In contrast, much less is known about the juvenile life history stages of *Sebastes*. Early post-settlement (juvenile) phases may be especially important to future recruitment to fisheries (Love et al., 1991). Although abundance of larvae is usually a poor indicator of future fishery stocks (Sissenwine, 1984), Bradford (1992) demonstrated reasonably precise forecasting of fishery-recruitment of four marine fishes from sampling post-larval life stages, and suggested that all life stages contribute significantly to variability in future stocks. Density-dependent regulation of fish stock abundance is likely in early demersal (nursery) habitats (Beverton et al., 1984), and mortality in early (juvenile) stages contributes importantly to the variability in recruitment to fisheries (Sissenwine, 1984).

Availability of appropriate settlement habitat is an important requirement for successful transition of marine fishes from pelagic to demersal stages (see review in Carr, 1991). For species with strongly substrate-oriented juvenile phases, limited nursery habitat may impose a demographic bottleneck (*sensu* Wahle and Steneck, 1991). Settlement and recruitment patterns, associations with habitat, food habits, and early benthic ecology are poorly understood for juvenile rockfishes in Washington waters (Norris, 1991).

Fishery managers often seek to exploit the habitat-survival link by creating super-normal artificial habitats to provide shelter, food, or other resources for important species (see review in Seaman and Sprague, 1991). Typically, however, these habitats are designed to attract adults for exploitation or fishery production, and little attention is paid to the habitat requirements of the pre-adult phase of target species (Bohnsack and Sutherland, 1985; Seaman et al., 1989; West et al., 1994).

In this study, we compare the patterns of settlement, recruitment, abundance, growth, and habitat associations of juveniles of a guild of three strongly substrate-associated rockfishes—copper (*S. caurinus*), quillback (*S. maliger*), and brown rockfish (*S. auriculatus*)—on two types of artificial nursery habitat. One type of reef was designed to provide refuge habitat for small, juvenile forms only, and the other to provide habitat for adults as well as juveniles. We tested functional differences of the reefs in terms of densities of juvenile rockfish they supported, without attempting to separate specific effects attributable to differential predation or habitat quality.

METHODS

Habitat

Studies were conducted on eight artificial reefs (two from each of four reef complexes) from October 1991 through May 1993 (Figure 1). The reefs are designated as follows: Gedney Island Artificial Reef Complex (GIARC), Boeing Creek Artificial Reef Complex (BCARC), Point Heyer Artificial Reef Complex (PHARC), and Misery Point Artificial Reef Complex (MPARC).

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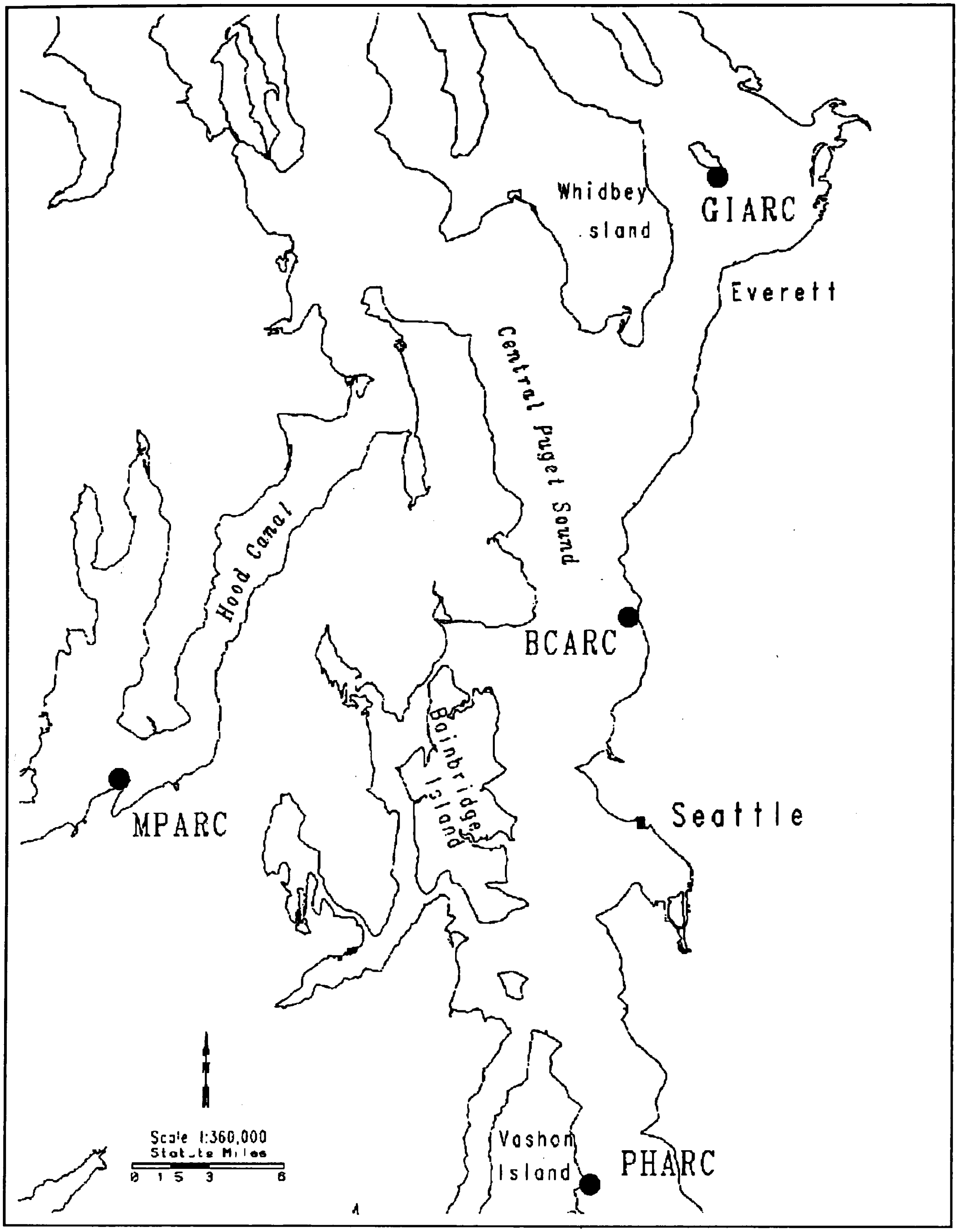

Figure 1. Location of study sites

Artificial reef complexes were constructed in March 1991, each with an integrated reef and an isolated nursery reef (Figure 2). Integrated Reefs consisted of a combination of older, high relief substrate and newer, low-relief rock (Figure 2). They were constructed by augmenting existing (aged eight to 11 years), high-relief, quarry boulder and concrete reefs with small-sized (ca. 8-20 cm dia.) quarry rock. The new quarry rock was configured in two to three bands originating at the shoreward margin of the existing high relief reefs, oriented perpendicular to, and running toward, the shoreline. A single band was also placed alongside (parallel to) the shoreward margin of each existing high-relief reef, forming a "skirt" of small rock.

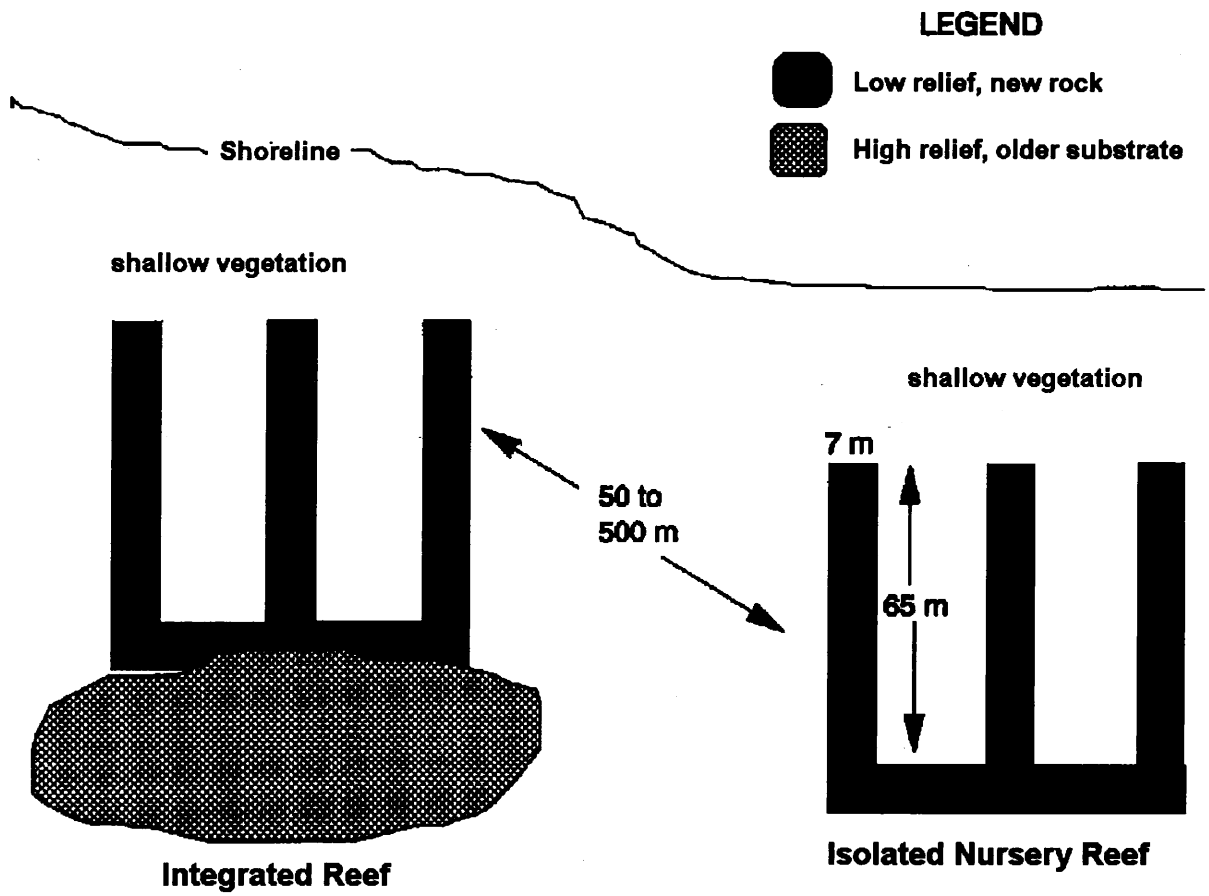

Figure 2. Schematic diagram of one artificial reef complex

The configuration of new, small rock described above was repeated between 50 m and 500 m away from each integrated reef on featureless sand substrate to create isolated nursery reefs. The width of low-relief quarry rock bands on nursery reefs was approximately 7 m, length ranged from 29 to 87 m, and vertical relief was less than 50 cm. Isolated nursery reefs consisted solely of new, low-relief rock. A more detailed description of reef construction and parameters is presented in West et al. (1994).

Fish Density

Visual census strip-transects were the basis for all density estimates in this study. Pairs of divers swam alongside transect lines, counting all rockfish observed in 5 m long by 2 m wide cells. Time spent by divers in each cell was variable, depending on the complexity of the substrate. Transect lengths varied from 40 m to 100 m. Rockfish were classified as young-of-the-year (YOY) 0 to 90 mm in total length (TL); subadults 100 to 180 mm TL; or adults >180 mm TL. Sizes were estimated visually underwater with the aid of diver-held scales.

Because of strong similarity in morphologic and morphometric characteristics, YOY copper and quillback rockfish less than about 70 mm TL are particularly difficult to distinguish, even in the laboratory. Although YOY brown rockfish were easier to identify visually in the field, these three species were grouped for all analyses. We also conducted aquarium grow-out studies at the Point Defiance Public Aquarium (Tacoma, Wash.) on representative samples of the indistinguishable copper/quillback YOY mix collected at the study sites and nearby natural habitats. This allowed us to ensure that the fish we observed were copper and quillback rockfish (this was the case) and to assess our ability to identify these species by sight as they grew. These fish were also used to measure growth of YOY (see below).

Divers measured depth (in feet) and noted substrate type within each cell. Depths were subsequently corrected to height (nearest meter) below mean lower low water (MLLW). For the distribution-by-depth analyses, mean density of a size class was computed for transect cells within 1 m isobaths. Substrate was recorded as "high" (older material with vertical relief to 2 m), "low" (new rock with vertical relief less than 0.75 m) or "mix" (where both substrate types occurred in a cell).

All transects were conducted during daylight hours, and integrated reef/nursery reef transect pairs were taken as close together in time as possible to minimize the potential confounding effects of time of day or tidal state. From the time of construction until the first recruitment of YOY, all reefs were monitored qualitatively for presence of YOY. Once YOY were observed on a reef, quantitative transects were initiated.

Data Analysis

Estimates of rockfish density were made in 540 cells from 22 pairs of nursery reef/integrated reef transects at the four artificial reef complexes over the course of this study. Size-class-specific densities were compared between substrate type (low substrate vs high substrate on integrated reefs) by using the Student's t value (SAS, 1985). Densities of rockfish between reef types (integrated vs nursery reefs) were compared using the Wilcoxon matched pair test of ranked densities (SAS, 1988).

For analysis of growth, rockfish YOY were collected from the BCARC nursery reefs three times over the course of the study. These fish were collected using hand-nets, measured and released at the site of capture. Some specimens were collected from natural nursery habitats and retained for aquarium growout at ambient seawater temperature in 1990 and 1991.

RESULTS

Recruitment, Settlement and Growth of YOY

YOY rockfish were first observed approximately 8 months after construction on the BCARC nursery reef, after 10 months at MPARC and GIARC, and after 12 months at PHARC. A unimodal size-frequency distribution was observed in each of three YOY collections made from the BCARC nursery reef over a nine-month period (Figure 3). In October 1991, mean TL (±SE) of YOY was 61±1.0 mm. After approximately seven months (May 1992) mean size of this cohort was 85±1.4 mm, representing an overall growth rate of 0.1 mm/day. More rapid growth was observed over the next two months (0.4 mm/day over 39 days), with a mean TL of 100±1.5 in July 1992. This pattern was also observed in aquarium growout specimens. Growth rate in captive specimens was 0.1 mm/day for November 1991 through February 1992 and increased to 0.3 mm/day in May through June 1992.

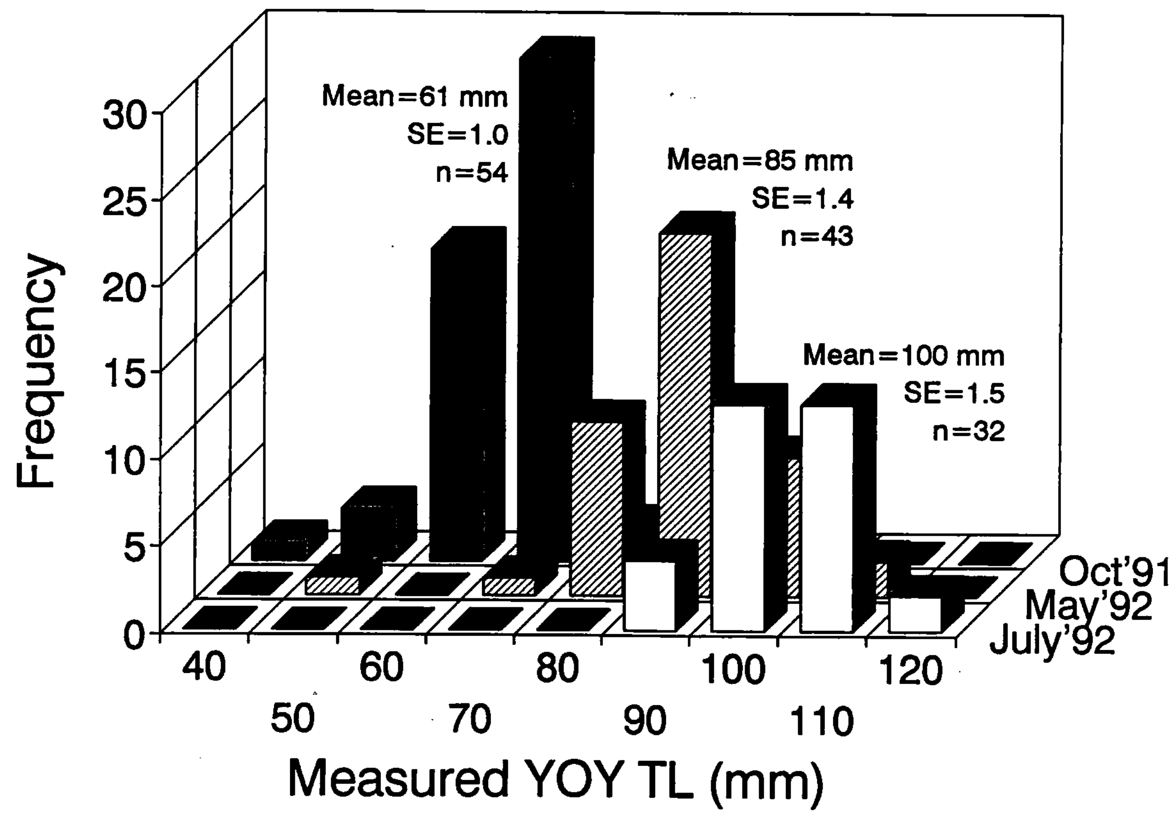

Figure 3. Growth of the 1991 YOY rockfish cohort from the BCARC nursery reef. Length-frequency distributions were determined from YOY collected, measured, and released on the reef.

Macroalgae and Depth

During settlement of YOY rockfish in 1991, macroalgae were virtually absent from most artificial reef complexes. In 1992, heavy stands of understory kelp (e.g., *Agarum fimbriatum, Laminaria saccharina, Costaria costata,* and *Desmarestia ligulata*) developed on shallow (low-relief) portions of all reefs, except the GIARC. Reefs in the GIARC were constructed in deeper water (greater than 12 m), which is beyond the normal depth for kelps. Dense stands of overstory bull kelp also developed at the BCARC, and the PHARC had a moderate abundance of bull kelp in 1992. The MPARC is located outside the normal geographic range for bull kelp in Washington state (Thom and Hallum, 1990). Low to moderate densities of foliose, fleshy red algae (e.g., *Sarcodiotheca* sp., *Rhodymenia pertusa, Gigartina exasperata,* and *Rhodoptilum* sp.) developed on all reefs by 1992.

At BCARC, where we observed substantial YOY recruitment in both years, the depth of low-relief substrate was 5 m to 20 m on the nursery reef. In October 1991, YOY rockfish recruited to this nursery reef primarily at the shallow ends of the shoreward bands, with the greatest densities in the 6 m isobath (Figure 4). We also observed YOY in the deepest transect cells measured (14 m) at the BCARC nursery reef. This cohort moved deeper in February and March 1992, with the greatest densities at depths of 10 m to 11 m (Figure 4). In 1992, when dense stands of bull kelp were present, newly recruited YOY oriented to the kelp stipes at the shallower ends of the bands and were not observed deeper than 10 m (Figure 4). When associated with kelp in this manner, YOY were often observed farther than 1 m above the substrate. In 1991, however, they remained closer to the rock-substrate and were seen most often within the interstices of the reef.

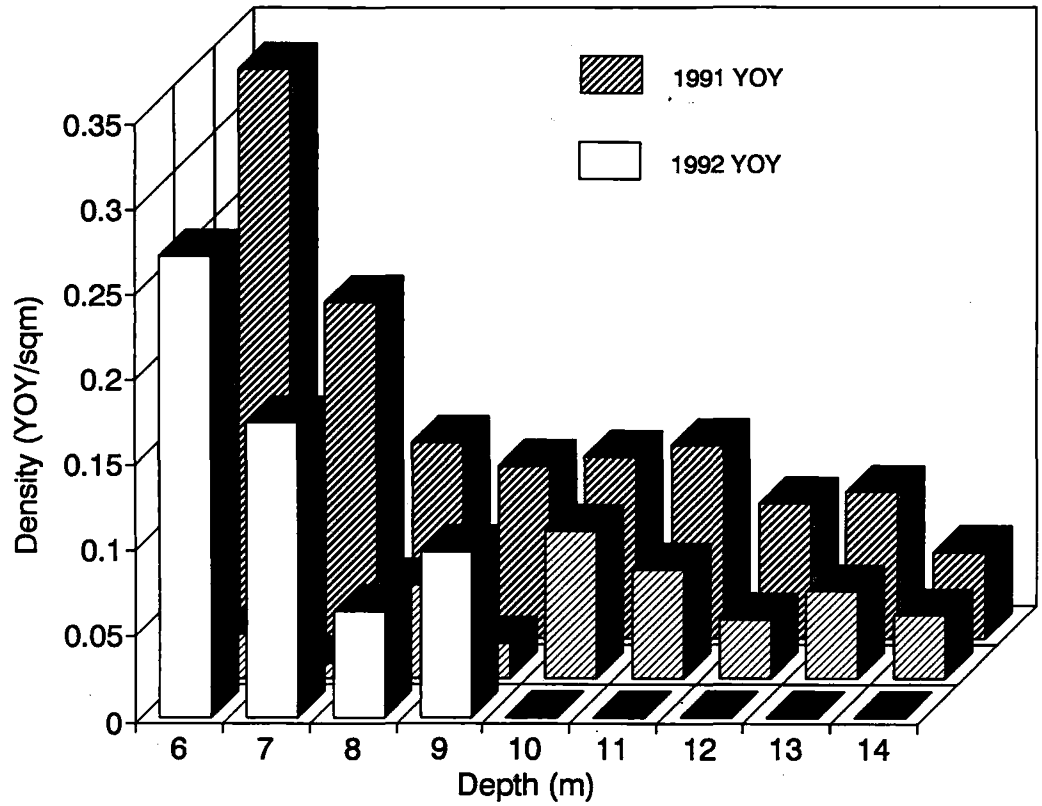

Figure 4. Distribution of YOY rockfish over depth and through time at the BCARC nursery reef

Habitat Associations

Size-classes of rockfish were segregated between our two reef types (Figure 5). For comparisons of average densities between reef types, YOY rockfish were significantly more abundant on nursery reefs than integrated reefs (Wilcoxon matched pair test of ranked mean transect densities, $p<0.05$; also most points fell below the parity line in Figure 5). Adult and subadult rockfish were significantly more abundant on integrated reefs (Wilcoxon matched pair test of ranked mean transect densities, $p<0.05$; also most points fell the above parity line in Figure 5). Subadults were the most abundant size class, and YOY and subadults were commonly observed on both reef types (Figure 5). Adult rockfish were rarely observed on nursery reefs (four of 22 transects).

On integrated reefs, where both low- and high-relief substrate were available to rockfish, we observed consistent segregation of YOY and adults by substrate type. For three out of four integrated reefs, YOY were significantly more abundant on the low-relief, small-size rock than on adjacent high-relief substrate (t test, $p<0.05$, Figure 6a). Integrated reefs at BCARC and MPARC showed significantly greater densities of subadult rockfish on high rock (t test, $p<0.0001$, Figure 6b), and the GIARC Integrated Reef had a significantly greater density of subadults on the low rock (t test, $p<0.05$, Figure 6a). All four integrated reefs exhibited greater densities of adult rockfish on high-relief substrate (t test, $p<0.0001$, Figure 6c).

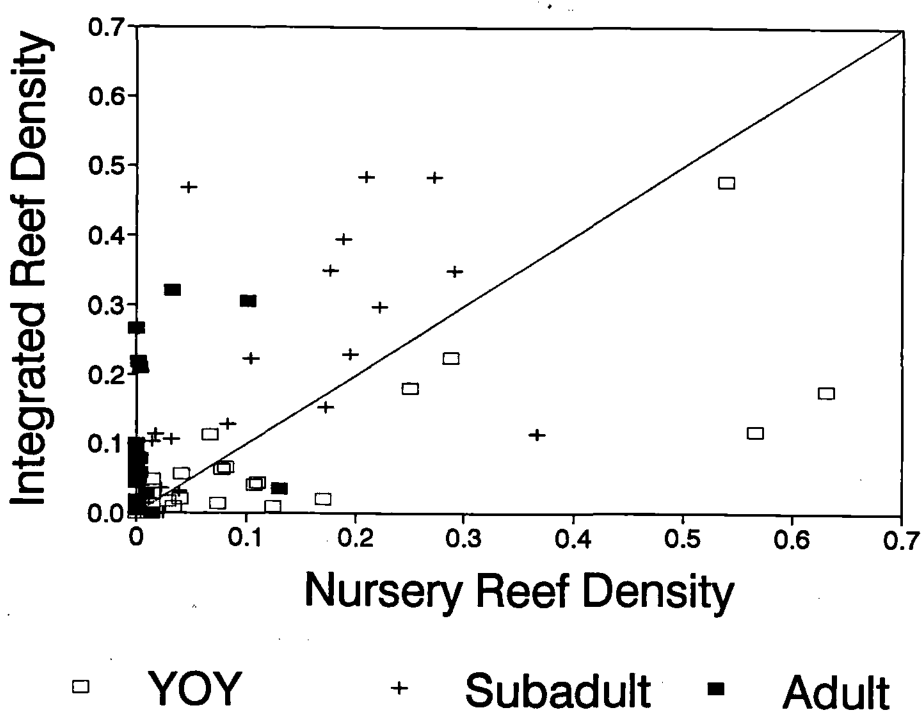

Figure 5. Segregation by size-class of rockfish between nursery and integrated reefs. The parity line of 1:1 slope indicates equal density between reef types for transect pairs.

DISCUSSION

Algal and seagrass habitats have been identified as fish nurseries in temperate ecosystems (Miller and Geibel, 1973; Larson and DeMartini, 1984; Carr, 1989; Holbrook et al., 1990). Vegetation such as eelgrass (*Zostera* spp.) and laminarian kelps (e.g., *Nereocystis luetkeana, Agarum* spp., *Laminaria* spp., *Costaria costatum* and *Desmarestia* spp.) is known to provide important settlement habitat for demersal rockfishes (Haldorson and Richards, 1986; Norris, 1991; Love et al., 1991). Thus, integrated and nursery reefs were constructed (where possible) with low-relief habitat shallow enough to abut existing eelgrass beds and to provide suitable substrate for the settlement and growth of large, foliose algae such as those mentioned above.

We were unable to determine whether YOY rockfish settled directly from the pelagic habitat to artificial reefs, or settled elsewhere and immigrated later. However, in 1992 (when substantial vegetation was present), YOY recruited to the reefs at a smaller size and earlier in the season than in 1991. We collected YOY from eelgrass beds contiguous with the BCARC in 1991; YOY may have settled to eelgrass, and then moved to nearby rock substrate as they grew. We have also observed YOY rockfish closely associated with submerged, detached drifting vegetation (as did Haldorson and Richards, 1987), near the artificial reefs. These drifting masses of detached algae and seagrass often became entrained by the rough surface of the reefs, and possibly provided YOY rockfish with a passive mode of transport, refuge, and food as they moved from vegetated settlement habitats to rocky substrates. The small size of 1992 YOY rockfish and their strong association with bull kelp on the artificial reefs, similar to size and behavior of YOY settling to natural nursery habitats (Doty et al., elsewhere in this proceedings) support an hypothesis that YOY settled directly to vegetated zones of the artificial reefs in 1992.

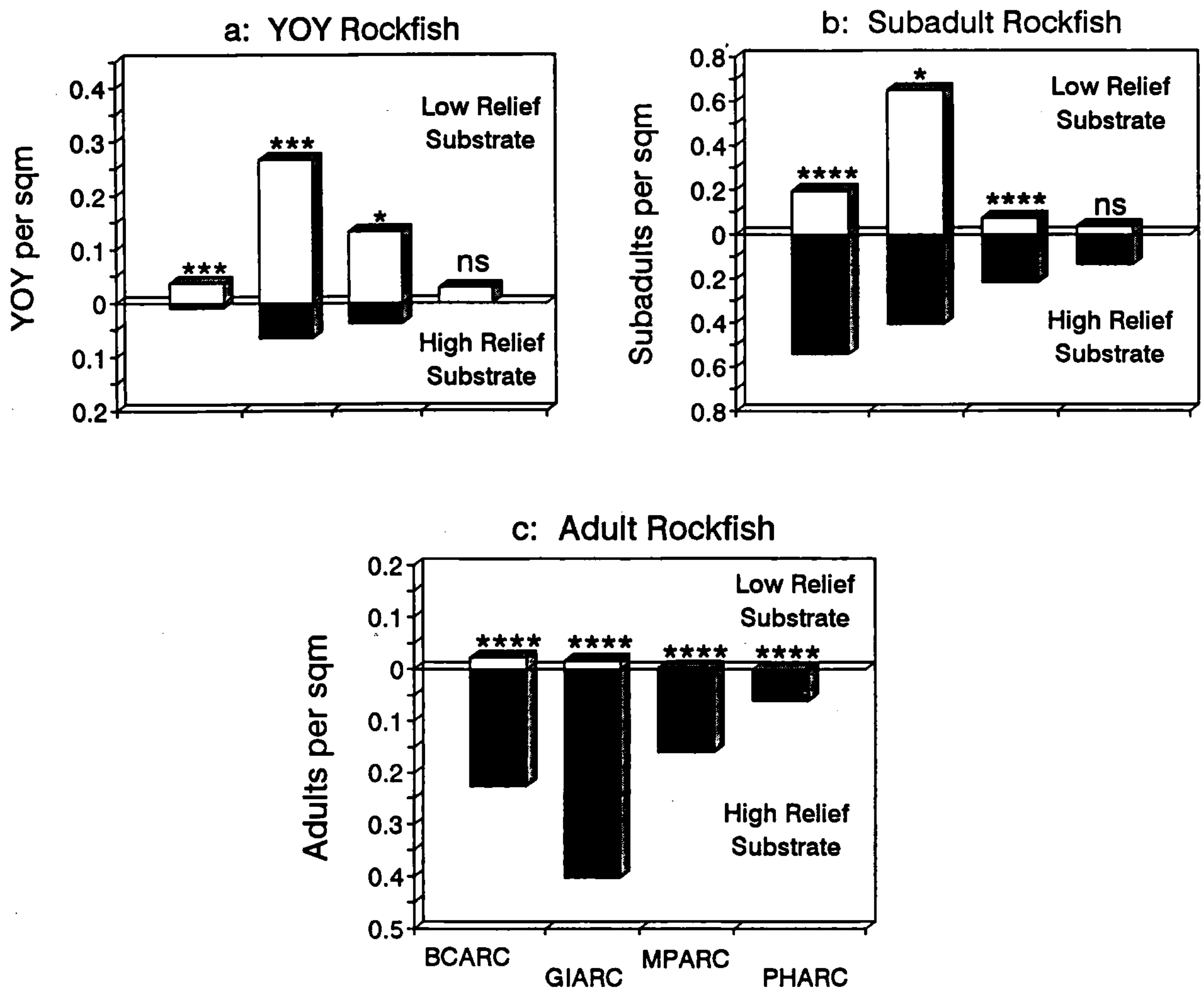

*Figure 6. Segregation by size-class of rockfish between low- and high-relief substrate on integrated reefs. Significance levels for Student's t test are as follows: ns=not significant ($p>0.05$); *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$; ****, $p<0.0001$.*

Geographic and temporal variability in the supply of settling juveniles contributed to the disparity of densities we observed among artificial reef locations. YOY rockfish were rare at the PHARC throughout the study until October 1992; they were also rare in natural rockfish habitats near the PHARC (Doty et al., elsewhere in this proceedings). In March 1993, we saw virtually no YOY at the MPARC, whereas we observed substantial numbers at the BCARC and GIARC. YOY rockfish recruited to three out of four artificial reef complexes in the first recruitment season subsequent to reef construction. That year (1991) also showed much greater YOY recruitment to natural habitats in Puget Sound than in 1992 (Doty et al., this volume).

Distribution of length-frequencies from YOY rockfish collected and released at a single site (BCARC nursery reef—Figure 3) supports a hypothesis of a single cohort recruiting to this location. Growth was high from the summer/fall recruitment until the winter, when growth slowed. Combined with our qualitative observations of YOY spending more time during the winter hiding within the reef interstices,

this indicates a period of relative inactivity during winter, perhaps because food is scarcer and temperatures lower. Winter hiding or torpor has been documented for other demersal temperate species and has resulted in apparent reductions in their density (Emery, 1978; Olla et al., 1974, 1975). During the second year of our study, the biomass of algae on the artificial reef complexes followed normal seasonal fluctuation patterns of a summer high and winter low biomass for the ecosystem. The reduction of algae-structure on the reefs in the winter may have reduced the supply of food foraging cover for YOY, potentially contributing to inactivity and a slowing of growth. Low winter temperatures may also directly reduce growth rate of YOY. Matthews (1988) reported temperature minima from January through April 1987 in Puget Sound roughly corresponding to our observations of slowed growth in YOY rockfish. Love et al. (1991) suggested that although food may be scarcer in winter, it is likely not limiting for YOY rockfish, and that temperature is the primary determinant of their rate of growth.

The presence of subadults on nursery reefs soon after construction suggests that older rockfish move over a larger area than YOY. Some older rockfish may be itinerant, roaming until they encounter suitable habitat. Buckley and Hueckel (1985) found that subadult and adult copper rockfish recruited to newly constructed artificial reefs within a few weeks, and observed quick replacement of adult rockfish removed from artificial reefs by fishing. Matthews (1990) documented subadult and adult copper, quillback and brown rockfish returning to home reefs after being displaced from 50 m to 8000 m, and suggested that rockfish on less suitable or inferior habitat wander until they encounter more favorable habitat. Hence, in this study, adult and subadult rockfish likely encountered nursery reefs soon after the reefs were constructed, yet only subadult rockfish remained on the low-relief substrate of the nursery reefs.

An important difference between the succession of rockfish populations at nursery reefs and integrated reefs is the pre-existence of established rockfish populations at the integrated reefs. At integrated reefs, new low-relief habitat was placed contiguous with the older, high-relief habitat. Thus, in addition to the recruitment potential of older immigrants and newly settling YOY, the new substrate had a ready pool of adult and subadult rockfishes on site. Nursery reefs were constructed in areas isolated from any substantial substrate structure and therefore were dependent solely upon immigration and settlement of rockfish. Adult rockfish clearly remained associated primarily with high-relief habitat on the integrated reefs, and they did not colonize nursery reefs. Although YOY rockfish recruited to both reef types, they were relatively scarce on integrated reefs.

There are many potential causes of the size-segregation we observed. For one, predation may be a significant factor in determining the distribution of YOY; however, the primary predators on YOY rockfish in this system remain unknown. Predators likely include lingcod (*Ophiodon elongatus*), which are known to consume rockfish (Cass et al., 1990). Lingcod were common on all integrated reefs, and rare on nursery reefs. We have observed adult quillback rockfish attack and eat YOY Puget Sound rockfish (*S. emphaeus*). Murie (1994) reported small numbers of rockfish prey in the stomachs of adult copper and quillback rockfishes. Adult and subadult rockfish are large enough to consume YOY, and therefore are considered potential predators on YOY ("circumstantial piscivores" of Hixon and Beets, 1993). Even if adult and subadult rockfish consume YOY only occasionally, their relatively high abundance could have a substantial impact on YOY rockfish. Thus, the overall greater number of potential predators on integrated reefs may reduce the number of YOY at those sites through (1) predation of YOY, (2) avoidance of predator-habitats by YOY and (3) avoidance of predation by hiding more within reef interstices, making YOY in the presence of predators (e.g., on the integrated reefs) more difficult to see and census accurately.

Perhaps the most significant result from our study is the segregation of YOY rockfish we observed between substrate type (large rock vs small rock) and between reef types (integrated reef vs isolated nursery reef). YOY rockfish were most abundant on low rock isolated from high-relief adult habitat (isolated nursery reef), followed by low rock adjacent to adult habitat (integrated reef); they were least abundant on adult habitat (integrated reef). Assuming that density of YOY rockfish (in this case) is an appropriate index of the relative suitability of their habitats, it appears that traditional artificial reefs constructed from large materials (e.g., rock and concrete boulders) provide suitable habitat for only older benthic phases in the life history of these species. Addition of habitat suitable for YOY and juvenile

rockfish to existing reefs (as in this study) or designing new reefs accounting for the habitat requirements of juveniles as well as adults might be a cost effective way to increase the enhancement potential of artificial reefs.

It is unknown how long YOY or subadult rockfish remain on the isolated nursery reefs. Tagging studies would allow us to determine whether rockfish leave the low-relief nursery reefs in search of higher-relief rocky reefs as the fish grow larger. Constructing nursery habitats from small-scale substrate isolated from adult habitats may discourage potential predators from colonizing the reefs (potentially reducing predation mortality on YOY); however, augmenting high-relief reefs with low rock may provide enough cover to reduce predation, while providing a more ready source of subadults for later recruitment to adult populations. Our study suggests that existing artificial reef systems targeting *Sebastes* spp. can be more finely tuned by providing refuge and foraging habitat for the complete demersal phase of target species.

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RECRUITMENT ECOLOGY OF JUVENILE ROCKFISHES (*Sebastes* spp.) IN DRIFT HABITAT IN THE SAN JUAN ARCHIPELAGO, WASHINGTON

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INTRODUCTION

Sebastes is the most speciose genus along the Pacific Coast of North America, ranging from 62 species off California (Hallacher and Roberts, 1985) to at least 35 species off British Columbia (Hart, 1980). The large complex of rockfish species forming the genus *Sebastes* produces one of the most abundant types of fish larvae in the north Pacific Ocean (Ahlstrom, 1961). The abundance of rockfish larvae in the plankton has also been noted in surveys conducted in Washington's inside waters, including Puget Sound (Waldron, 1972). There have been 26 species of rockfish recorded from these inside waters (Miller and Borton, 1980).

Sebastes have major ecosystem importance throughout their ranges. Many rockfishes support large recreational and commercial fisheries, and catches and stock status are regularly monitored in management programs. Eight species of *Sebastes* are designated as "management species" in the Groundfish Management Plan for Washington's Inside Waters (Pedersen and DiDonato, 1982). Many larval and juvenile rockfishes have substantial trophic value in pelagic ecosystems as food for a variety of fishes ranging from chinook salmon (*Oncorhynchus tschawytscha*; i.e., Ralston, 1990) to tunas (Scombridae; i.e., Pinkas et al., 1971). Juvenile rockfishes also have trophic value in benthic ecosystems for numerous piscivors, including lingcod (*Ophiodon elongatus*; Hallacher and Roberts, 1985) and undoubtedly sculpins (Cottidae), but infrequently through intra-generic predation, except in some density-dependent situations in coastal California ecosystems (Hallacher and Roberts, 1985). Some rockfishes are important predators in structuring nearshore ecosystems in Puget Sound (Hueckel and Buckley, 1987), and at least one, quillback rockfish (*S. maliger*), may have a keystone role on these rocky reefs in the rapid transfer of energy resources provided by the short trophic linkage from algae and seagrass to pandalid shrimp (second author, unpublished).

Sebastes are viviparous, and after parturition, the pelagic phase for the larvae is temporally and spatially variable. Relatively little is known about larval ecology or that of the older planktonic juveniles, except that they are widely distributed, often considerable distances from the benthic adult habitats (Moser and Boehlert, 1991). At the time of settlement from the plankton, juvenile rockfishes become strongly associated with various substrates in the local habitat; substrate type differs markedly among species (e.g., algae, rock, sand, mud; Love et al., 1991). This transition from planktonic juveniles to substrate-associated juveniles often involves one or more intermediate pelagic habitats for several species, before the juveniles become associated with benthic substrates or attached algae and seagrass.

Many rockfishes in the eastern and western Pacific Ocean recruit from the plankton to drift mats of kelp and other macro-algae, and seagrass (Mitchell and Hunter, 1970; Boehlert, 1977; Fedoryako, 1989; Safran and Omori, 1990), and occasionally other flotsam (Hitz, 1961), apparently as the first substrate association. Juvenile splitnose rockfish (*S. diploproa*) undergo transitions from surface mats of algae to mid-water habitats, possibly for periods up to several months, before association with benthic habitats (Boehlert, 1977). Some of the time in mid-water habitats may be the result of migration from algal mats over deep water and subsequent horizontal movement to benthic habitats at appropriate depths.

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Drift algae and seagrass provide habitat structure in the open pelagic environment that affects the distributions, movements, survivorship, and recruitment patterns of juvenile fishes, through their aggregation and colonization from the plankton and transportation with the habitat (Dooley, 1972; Kingsford and Choat, 1985; Safran and Omori, 1990; Kingsford, 1992). Internal waves, tidal currents, surface winds, and other physical processes aggregate scattered distributions of drift algae and seagrass into concentrations or mats of habitat (Kingsford and Choat, 1986). Surface slicks from internal waves and tidal currents also concentrate zooplankton in these areas (Franks, 1992). The drift mats of algae-seagrass (hereafter also called drift habitat) form pelagic nursery areas for juvenile fishes, which provide both refuge and abundant food resources, the latter through the invertebrate epifauna on the algae and the close proximity to concentrations of zooplankton (Kulczycki et al., 1981; Kingsford and Choat, 1985; Gorelova and Fedoryako, 1986; Wright, 1989).

The unusual pelagic ecosystem of drift habitat and the importance of this habitat to juvenile rockfishes have never been examined in detail in Washington's marine waters. Preliminary studies in this region have shown that drift mats of algae-seagrass are used as refuge habitat by at least two juvenile rockfishes (splitnose rockfish and tiger rockfish, *S. nigrocintus*), and that the juvenile splitnose rockfish feed heavily on the associated epifauna and zooplankton (Washington Department of Fish and Wildlife, unpublished). The preliminary trophic study examined drift habitat during June, August, and October 1992. It was unknown whether this habitat was present and utilized by possibly additional species of juvenile rockfish in other months of the year. The objective of this study was to assess the temporal cycle and algae-seagrass composition of drift habitat in Washington's inside waters, and the recruitment of planktonic juvenile rockfishes to this habitat as the first substrate-associated phase of the settlement process. This would provide baseline information on the ecological value of this pelagic habitat, as well as information on the potential for effects on this habitat and the associated fauna from environmental impacts affecting the surface marine waters in the region.

METHODS

Sampling of drift habitat was conducted over the period of June 1992 through August 1994 in the Strait of Juan de Fuca and the San Juan Archipelago (Figure 1). Samples from June-October 1992, February, June, and August 1993, and August 1994 were made using a dip net with a 2.25 m long handle, a net opening 75 cm long x 35 cm wide, and a 55 cm deep bag of 3.2 mm mesh. Samples from July and September-December 1993, and January-June 1994 were made using a 15.2 m long x 3.7 m deep purse seine of 3.2 mm mesh. Samples from June and July 1994 were made using a 30.4 m long x 7.6 m deep purse seine of 3.2 mm mesh. Both dip net and purse seine samples were made during April-July 1994.

All samples were taken during daylight hours from small vessels. The locations and times of the samples were haphazardly selected, often based on the occurrence of calm weather and tidal conditions, and in proximity to other priority research activities. On any sampling day, samples were taken from randomly encountered drift mats of algae-seagrass, either working into prevailing tidal currents and winds, or moving considerable distances between samples to prevent repeated sampling of the same algae-seagrass. Usually the sampled mats encompassed the range of sizes of drifting mats that were encountered during a day.

Dip net samples ranged from entire small mats of surface algae-seagrass, to only fractions of the volumes of large mats. Samples were made by moving the dip net upward through a mat to the surface, capturing as much algae-seagrass as practical in the net bag. Any large algae extending out of the net were cut with a knife, and then the samples were placed in tubs of sea water for careful washing and hand sorting. Purse seine samples were made by surrounding an entire drifting mat with the net and then pursing the net to capture all the algae-seagrass. Large algae were hand sorted, washed and removed from the net outboard of the vessel, and the remaining algae-seagrass were placed in tubs of sea water for careful washing and hand sorting.

Algae and seagrasses in the samples were identified to the lowest practical taxonomic level. The amounts of algae and seagrass in purse seine samples were quantified by loose volume in containers; large

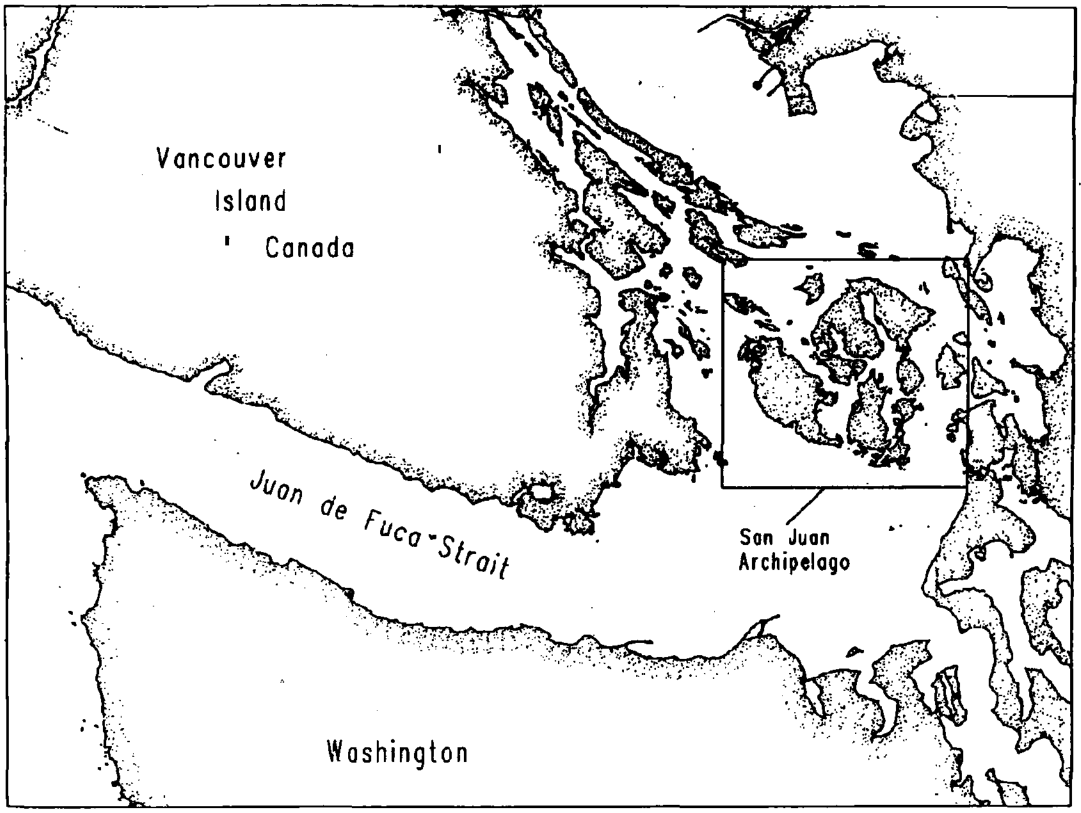

Figure 1. Washington's inside waters showing Juan de Fuca Strait and San Juan Archipelago regions sampled for drift mats of algae-seagrass

algae that could not be placed in containers without being cut into pieces were counted. Juvenile rockfish were identified to species and counted, and their total length (TL) was measured to the nearest mm.

RESULTS

The June 1992 to July 1994 sampling of drift habitat found 12 genera of algae and two genera of seagrasses, 11 identifiable to species, and 10 present in both Juan de Fuca Strait and San Juan Archipelago samples (Table 1; Figure 1). The 1992 dip net samples contained eight genera of algae and two seagrasses; one algal species, *Postelsia palmaeformis*, was rare in the drift mats as it was found in only one sample. Purse seine samples of complete mats in 1993 and 1994 added only four species of algae, including another species, *Pterygophora californica*, found in only one sample.

The seasonal algae-seagrass composition of drift mats was quantified in purse seine samples from July 1993 to July 1994 in Juan de Fuca Strait and the San Juan Archipelago (Table 2). These samples found drift habitat present in all months in this region, composed primarily of *Nereocystis luetkeana* (bull kelp), *Macrocystis* sp. (giant kelp), *Zostera marina* (eelgrass), and *Fucus distichus* (rockweed). The apparent absence of *Macrocystis* during some months (Table 2) reflects a lack of samples in western Juan de Fuca Strait, the eastern limit of the natural range for this algae. The remaining one genus and seven species of algae, and one genus of seagrass, were present irregularly in moderate to trace amounts, indicating possible temporal limitations.

Table 1. Algae-seagrass present[1] in drift habitat samples[2] from June 1992 to July 1994 in Juan de Fuca Strait and the San Juan Archipelago

	1992 June-Oct.	June-Dec.	1993 Feb. Jan.-July	1994 Total		1992-1994		
ALGAE-SEAGRASS [Code][3]	JdFS[4]	SJA[4]	JdFS	SJA	JdFS	SJA	JdFS	SJA
Nereocystis luetkeana [Nl]	X	X	X	X	X	X	X	X
Macrocystis sp. [Msp.]	X		X		X		X	
Zostera marina [Zm]	X	X	X	X	X	X	X	X
Fucus distichus [Fd]	X	X	X	X	X	X	X	X
Ulva sp. [Usp.] X	X		X	X	X	X	X	
Sargassum filipendula [Sf]		X	X	X	X	X	X	X
Phyllospadix sp. [Psp.]	X		X		X	X	X	X
Egregia laevigata [El]	X		X		X	X	X	X
Entermorpha intestinalis [Ei]	X		X			X	X	X
Costaria costata [Cc]			X			X	X	X
Desmarestia munda [Dm]			X			X	X	X
Postelsia palmaeformis [Pp]	X						X	
Alaria nana [An]			X				X	
Pterygophora californica [Pc]						X		X

[1] X = present in sample.
[2] Dip net: June-October 1992; February, June, August 1993; April-July 1994.
Purse seine: July, September-December 1993; January-July 1994.
[3] Genus/species code used in Table 2 and Figure 2.
[4] JdFS = Juan de Fuca Strait; SJA = San Juan Archipelago.

Table 2. Contributions[1] of algae-seagrass to drift habitat during July 1993 to July 1994 purse seine sampling; Juan de Fuca Strait and San Juan Archipelago combined

	1993					1994						
ALGAE[2]	July	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
Nl[3]	62.1	18.2	5.3	22.7	12.8	23.4	13.3	4.3	16.5	29.3	97.5	34.8
Msp.	19.0	50.6	0	0	0	356.5	0	58.2	0	204.2	0	0
Zm	52.0	34.8	18.6	21.3	16.6	0.3	11.4	0.2	1.8	13.0	36.4	29.1
Fd	13.3	9.7	19.7	4.3	0	0	0.4	0	6.8	28.2	29.7	47.9
Usp.	0	0.3	0.2	0	0	0	0	0	0.3	0.2	0.4	0.1
Sf	0.9	0.2	0	0	0	0	0.1	0	0	0.2	0.6	1.5
Psp.	0	0	0	0	0	0	0	0	0	0	0.1	0
El	0.1	0.2	0	0	0	0.4	0.1	0.3	0.3	0.5	0	0
Ei	0.1	0	0	0	0	0	0	0	0	0	0.3	0
Cc	0.1	0.1	0	0	0	0	0	0	0	0	2.0	0.3
Dm	0	1.7	0	0	0	0	0	0	0	0	2.3	0
An	0	0.1	0	0	0	0	0	0	0	0	0	0
Pc	0	0	0	0	0	0	0	0	0	0	0.1	0
n[4]	7	6	3	3	4	5	4	3	2	3	4	4

[1] Average volume in l, except Nl -*Nereocystis luetkeana.*
[2] Algae-seagrass codes from Table 1.
[3] July 1993: Average volume in l.
September 1993 to July 1994: Average number of plants.
[4] Number of purse seine sets.

The structure of the drift habitat ranged from small clumps of a single species of algae-seagrass (most often *F. distichus* or *Z. marina*) at the surface, to large, complex, cohering mats of many species that had three general zones of density and depth (Figure 2). The dense surface mat (Zone 1) extended to a depth of 0.5 m and was held together primarily by entangled stipes, pneumatocysts and fronds of *N. luetkeana* and *Macrocystis* sp., which retained often large amounts of other algae-seagrass. The moderately dense area under the surface mat (Zone 2) extended to a depth of 1.0-1.5 m and was composed of *N. luetkeana* fronds and non-floating sections of primarily *Macrocystis* sp., *Sargassum filipendula*, and *Egregia laevigata* that were supported by the surface mat. The central column of the mat (Zone 3) extended to a depth of up to 3.0-4.0 m and was composed of entangled stipes and holdfasts of *N. luetkeana* that were weighted down by benthic material still grasped by holdfasts.

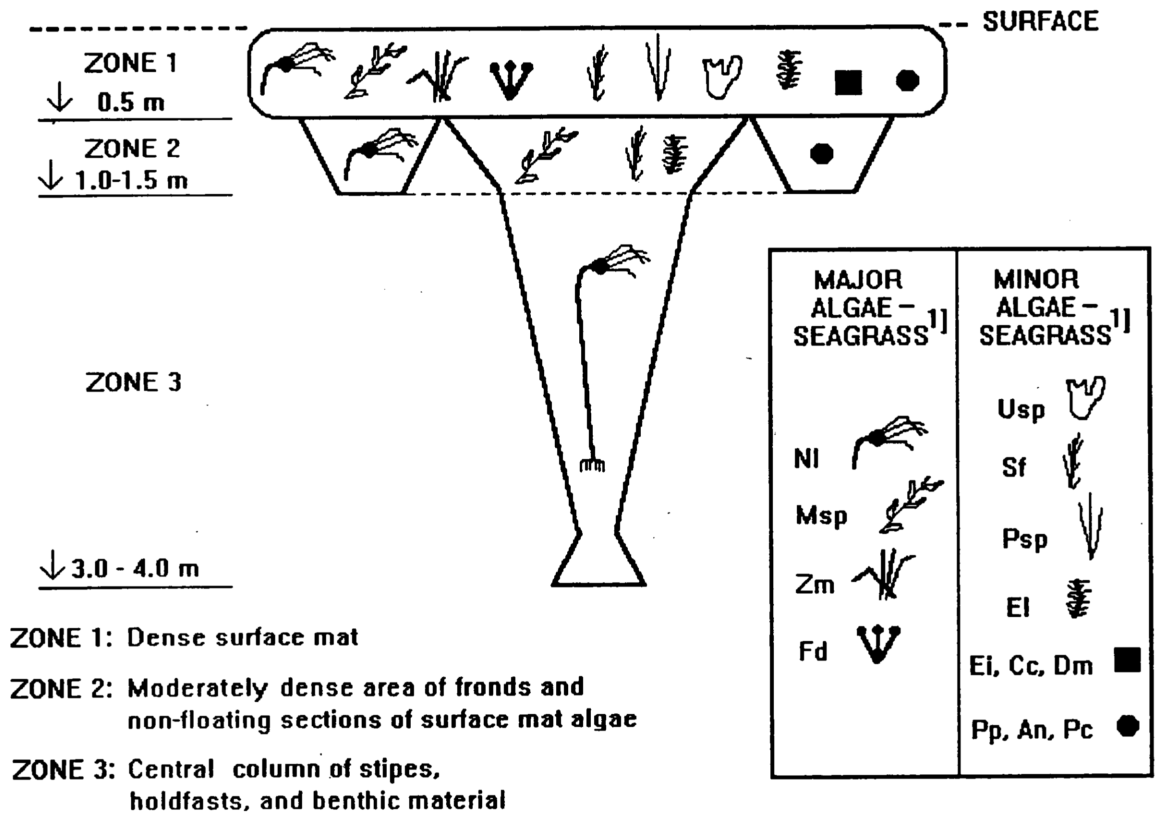

Figure 2. Diagram of the structure of drift habitat showing the algae-seagrass composition of the three general depth zones (1] Algae-seagrass codes from Table 1)

Both dip net and purse seine sampling techniques were successful in capturing juvenile *Sebastes* in drift habitat in Juan de Fuca Strait and the San Juan Archipelago (Table 3). Juvenile rockfishes were found in the drift habitat during June and remained in this habitat until November. During these months, dip net samples (n=179) averaged 3.0 juvenile rockfishes per sample, while the more efficient purse seine samples (n=28) averaged 22.3 juveniles per sample. Juvenile rockfishes were not found in drift habitat in February 1993 and from December 1993 through May 1994, except for a single fish found in January 1994.

Table 3. Frequency of dip net and purse seine samples and numbers of juvenile Sebastes *recovered from drift mats of algae-seagrass in Juan de Fuca Strait and the San Juan Archipelago, June 1992 to August 1994*

YEAR	MONTH	n	GEAR	LOCATION[1]	# FISH
1992	June	≥3	Dip Net	SJA	27
	July	83	Dip Net	JdFS, SJA	224
	Aug.	43	Dip Net	JdFS, SJA	186
	Sept.	9	Dip Net	SJA	44
	Oct.	6	Dip Net	SJA	15
1993	Feb.	28	Dip Net	SJA	0
	June	12	Dip Net	SJA	26
	July	7	Purse Seine	JdFS, SJA	260
	Aug.	≥1	Dip Net	JdFS	13
	Sept.	6	Purse Seine	JdFS, SJA	75
	Oct.	3	Purse Seine	SJA	91
	Nov.	4	Purse Seine	SJA	193
	Dec.	5	Purse Seine	SJA	0
1994	Jan.	5	Purse Seine	JdFS	1
	Feb.	4	Purse Seine	SJA	0
	Mar.	3	Purse Seine	JdFS	0
	Apr.	2	Purse Seine	SJA	0
	Apr.	24	Dip Net	SJA	0
	May	7	Purse Seine	JdFS, SJA	0
	May	5	Dip Net	JdFS, SJA	0
	June	4	Purse Seine	SJA	5
	June	7	Dip Net	JdFS, SJA	0
	July	4	Purse Seine	SJA	0
	July	10	Dip Net	SJA	2
	Aug.	≥5	Dip Net	SJA	8

[1] SJA = San Juan Archipelago.
JdFS = Juan de Fuca Strait.

Splitnose rockfish juveniles comprised 96 percent (n=1,123) of the juvenile rockfishes captured in drift habitat in Juan de Fuca Strait and the San Juan Archipelago (Table 4). This species recruited from the plankton to the drift habitat at 12-15 mm TL in 1992 and 1993 and were present at this size in August 1992 and October 1993, indicating protracted recruitment periods. The 13 mm TL juvenile in October 1993 may be an anomaly, as the next smallest fish captured in this month was 19 mm TL. Splitnose rockfish were present at these small sizes in drift habitat in June 1992 and June 1993, which were the first months sampled in these years. In 1994 they first appeared in June, whereas juveniles had not been found during the preceding six months. This indicates that juvenile splitnose rockfish first recruit from the plankton to drift habitat during June in this region. The lack of these small juveniles after August in 1992 and 1993, combined with monthly increases in the lower ends of the size ranges starting in September of both years (Table 4), reflects a recruitment period of June through August.

The average sizes of juvenile splitnose rockfish in the drift habitat increased from June to October 1992 and from June to November 1993, indicating feeding and growth in this habitat (Figure 3; Table 4). The average monthly growth rates during these periods were 2.78±1.08 mm TL (±standard error - SE; r^2=0.69) in 1992, and 2.63±0.65 mm TL (±SE; r^2=0.80) in 1993. The maximum sizes of the juveniles in the drift habitat was 51 mm TL in 1992 and 1994, and 49 mm TL in 1993, and appeared to be reached by August. These maximum sized fish were not found in samples after August in 1992 and 1993, and there appears to be a general decrease in the maximum size of splitnose rockfish juveniles in drift habitat during later

*Table 4. Number and size of juvenile splitnose rockfish (*Sebastes diplopora*) recovered from drift mats of algae-seagrass in Juan de Fuca Strait and the San Juan Archipelago, June 1992 to August 1994*

YEAR	MONTH	#FISH	RANGE[1]	AVERAGE[1]	STD.[2]
1992	June	26	14-42	19.8	6.5
	July	219	13-47	28.3	7.3
	Aug.	177	12-51	32.5	8.4
	Sept.	44	18-47	30.7	8.1
	Oct.	15	22-41	32.5	5.3
1993	June	19	15-30	22.5	4.5
	July	238	14-43	29.6	7.4
	Aug.	11	15-49	24.9	9.5
	Sept.	75	18-44	30.9	7.0
	Oct.	91	13,19-47[3]	33.0	6.3
	Nov.	193	26-48	37.7	5.4
1994	Jan.	1		44.0	
	June	5	17-21	19.0	1.4
	July	1		33.0	
	Aug.	8	31-51	39.3	6.3

[1] Total length in mm.
[2] Standard deviation.
[3] Continuous length frequency distribution from 19-47 mm TL.

months (Table 4). The monthly sampling from June 1992 to August 1994 showed a residence time of June through November for splitnose rockfish in drift habitat in this region (Table 3).

Tiger rockfish juveniles comprised 4 percent (n=47) of the juvenile rockfishes captured in drift habitat in Juan de Fuca Strait and the San Juan Archipelago (Table 5). This species appeared to recruit from the plankton to drift habitat at 24-28 mm TL, as they were present at this size during June-July 1992 and June-August 1994. The start of recruitment of tiger rockfish juveniles to drift habitat in this region cannot be established accurately, as sample sizes are small; however, the lack of juveniles in the purse seine samples from September 1993 to June 1994 indicates that recruitment earlier than June is unlikely. The estimate of recruitment occurring at 28 mm TL indicates a protracted recruitment period of June-August.

The average sizes of tiger rockfish juveniles in drift habitat seemed to increase from June to August in 1992 and 1993, indicating feeding and growth, but the July 1993 sample of 22 fish provides the only reliable length frequency information (Table 5). The largest tiger rockfish juvenile was 53 mm TL, which may be approaching the maximum size reached in drift habitat. The residence time for tiger rockfish in this habitat appears to be June through August in this region (Table 3).

DISCUSSION

The unstratified sampling program and the use of both dip net and purse seine sampling gear prevent any detailed inter-annual and inter-regional comparisons of the species of algae-seagrass in the drift mats. The dip net was designed to capture juvenile *Sebastes*, and could be used only to note the species of algae-seagrass present in the dip net samples; most of the drift mats were too large and physically complex, and many of the algae too large, to be adequately sampled in the 0.7 m^3 volume of the dip net. However, the 71.4 percent overlap of types of algae-seagrass (10 of 14) between dip net and purse seine indicates that the dip net samples adequately represented the algae-seagrass complex found in drift mats in Juan de Fuca Strait and the San Juan Archipelago.

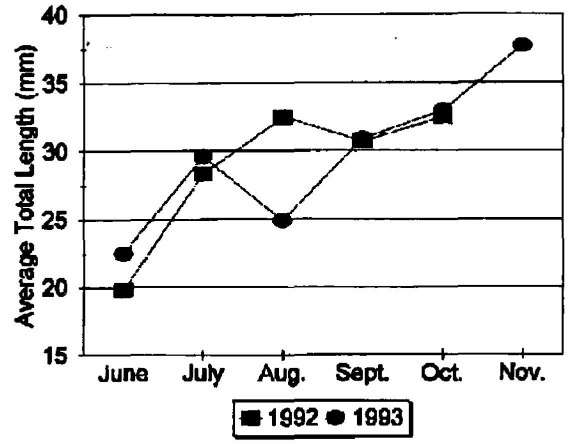

Figure 3. Average sizes of splitnose rockfish (Sebastes diplopora) *sampled in drift habitat, June-October 1992 and June-November 1993*

Tidal currents create substantial exchanges of drifting material between eastern Juan de Fuca Strait and the San Juan Archipelago (Figure 1); therefore samples from both areas were combined to develop an overall assessment of the temporal cycle and algae-seagrass composition of the drift habitat. This exchange is supported by the 10 types of algae-seagrass common to samples from both areas. The two algae not found in the San Juan Archipelago samples, *Macrocystis* sp. and *P. palmaeforis*, are present as attached macrophytes only in extreme western Juan de Fuca Strait. The purse seine enabled quantification of all the algae-seagrass in the drift mats sampled; however, the distribution and frequency of this sampling was inadequate for refined assessments of any spatial and temporal variations. The 1993 and 1994 sampling confirmed that drift habitat is present in the region throughout the year and that there is little variation in the algae-seagrass composition of the mats. *N. luetkeana* (bull kelp), *Macrocystis* sp. (giant kelp), *Z. marina* (eelgrass), and *F. distichus* (rockweed) formed an estimated 98 percent to 100 percent of the volume of drift mats throughout the 1992-1994 sampling (see Table 2).

Table 5. Number and size of juvenile tiger rockfish (Sebastes nigrocintus) *recovered from drift mats of algae-seagrass in Juan de Fuca Strait and the San Juan Archipelago, June 1992 to July 1994*

YEAR	MONTH	#FISH	RANGE[1]	AVERAGE[1]	STD.[2]
1992	June	1		28.0	
	July	5	24-35	29.0	4.2
	Aug.	9	31-53	39.7	5.9
1993	June	7	27-31	28.1	1.6
	July	22	28-47	35.2	4.7
	Aug.	2	28-30	29.0	1.0
1994	July	1		31.0	

[1] Total length in mm.
[2] Standard deviation.

Dip net and purse seine samples captured the same size ranges of juvenile rockfishes in drift habitat (Tables 3 and 4); therefore, both types of data were combined for inter-annual comparisons of *Sebastes* recruitment ecology in this habitat. The small number of juvenile rockfishes captured during June-August 1994 (n=15) with substantial sampling effort (22 dip net and eight purse seine samples), compared to the large numbers captured during these months in 1992 (n=437) and 1993 (n=299), indicates that recruitment of splitnose rockfish (96 percent of total) in 1992 and 1993 was considerably stronger than in 1994 in this region (Table 3). It is not known whether this apparent variation in cohort strength is part of a normal cycle, or whether it is an artifact of later recruitment in 1994 that was missed by cessation of sampling in August.

Recruitment of splitnose rockfish to drift habitat in Juan de Fuca Strait and the San Juan Archipelago during June through August, as well as the residence time of juveniles in this habitat from June through November in this region, differs from the ecology of this species in drift habitat in southern California waters. In California's warmer oceanic ecosystem, juvenile splitnose rockfish recruited to drift habitat (primarily *M. pyrifera*) during February-March and July-December, and were present in drift habitat in all months (Boehlert, 1977). The size of these juveniles at recruitment from the plankton to the drift habitat was 10-15 mm standard length (SL; approximately 12-18 mm TL; Washington Department of Fish and Wildlife, unpublished), which is comparable to the 12-15 mm TL recruitment size found in Washington's inside waters in 1992 and 1993 (Table 4).

Splitnose rockfish juveniles settle from the drift habitat to the adult benthic habitat depths of 91-578 m throughout their range (Hart, 1980). In California waters, this migration appears to occur at 41-49 mm SL (approximately 47-57 mm TL) primarily during May and June; however, juveniles of settlement size are present throughout the year (Boehlert, 1977). In Juan de Fuca Strait and the San Juan Archipelago, migration from the drift habitat to (apparently) deeper water appears to occur primarily at >49-51 mm TL, and from August-November; however, the disappearance of juveniles after November, when 26 mm TL juveniles were present, indicates that this migration also occurs at much smaller sizes (Table 4). Based on the general rule that the principal parturition season for *Sebastes* is shorter and later in northern waters compared to southern waters, Boehlert (1977) anticipated that in northern waters the residence time of juvenile spiltnose rockfish in drift habitat would be more distinct, and the migration from surface waters would be more precise. This is verified by the timing found in these more northern waters; however, migration in this region must also be cued by one or more environmental parameters (e.g., season, temperature) in addition to body size, or there would be progressive growth of the smaller juveniles in the drift habitat in November to the migration size.

The growth rate of juvenile spiltnose rockfish in California waters was estimated as 5.7 mm month^{-1}, and was found to increase from 4.5 to 6.3 mm month^{-1} with a temperature increase of 10 to 15 C under laboratory conditions (Boehlert, 1981). The growth rates of 2.6-2.8 mm month^{-1} for juvenile splitnose rockfish in the colder waters of Juan de Fuca Strait and the San Juan Archipelago may be expected to be lower, but they seem to indicate that another parameter other than temperature, possibly trophic or metabolic energy needs, may be affecting growth rates in this region. The maximum size of the juveniles found in drift habitat in California, 55 mm SL (approximately 63 mm TL), was also considerably larger that the maximum of 51 mm TL found in Washington waters.

Drift mats of algae-seagrass in Juan de Fuca Strait and the San Juan Archipelago function as refuge and feeding habitats for juvenile *Sebastes*, and as an intermediate recruitment pathway to other habitats for splitnose and tiger rockfish, and possibly other rockfishes. This indicates that drift habitat is an important, and possibly obligate, recruitment habitat for some juvenile rockfishes. Drift habitat is spatially and somewhat temporally limited in these temperate waters, and the amount of this habitat may be severely limited and decreasing annually in some areas due to increasing perturbations of marine shorelines and nearshore areas, which are the sources of the algae and seagrass. The ecological functions of both the attached and drift habitats formed by algae-seagrass must be given consideration when evaluating environmental impacts.

Detached algae and seagrass are aggregated in frontal zones by oceanographic and atmospheric forces, where they are concentrated into drift habitat (Harrold and Lisin, 1989; Kingsford, 1992). Frontal zones also accumulate planktonic biota, creating areas of enhanced biomass (Shanks, 1988; Franks, 1992), and aggregate and retain many forms of polluting agents that can adversely affect both the drift algae-seagrass and the associated biota. Oil spilled in the marine environment will accumulate in the areas of drift habitat concentrations. The major algae-seagrass components of the drift habitat are sensitive to oil and dispersants (Stekoll et al., 1993; Thom et al., 1993). Oil can adhere to *N. luetkeana*, causing necrosis of the pneumatocyst and stipe. This results in premature sinking, which affects the integrity of the drift habitat (Washington Department of Fish and Wildlife, unpublished). Many of the epiphytic and planktonic organisms associated with drift habitat that are food items for juvenile rockfishes are extremely sensitive to both oil and dispersants (Rosenthal, 1976; Wilson, 1977; Corell, 1989). Juvenile rockfishes are also undoubtedly sensitive to these substances (see Blaxter and Hallers-Tjabbes, 1992). Burning oil *in situ* will destroy the drift habitat and all the associated biota, although this impact is not considered in the evaluation of this clean-up option (see Anon., 1994). These factors have policy implications for evaluation of environmental impacts in surface marine waters, especially for resource damage assessments from oil spills and for related clean-up management decisions involving the use of dispersants and *in situ* burning.

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NEARSHORE INDUSTRIALIZED AREAS OF PORT GARDNER, WASHINGTON, AND THEIR EFFECTS ON EARLY MARINE LIFE HISTORY OF ANADROMOUS FISH

J.P. Houghton[1], M.A. Kyte[1] and D.L. Gregoire[2]

INTRODUCTION

The Snohomish River is the second-largest watershed draining into Puget Sound (Figure 1). Historically, the river discharged onto Port Gardner via several distributary channels, which meandered continually through a growing delta of shallow mud or sand flats. Since the late 1800s, Port Gardner has become an important deep-water harbor critical to the economy of Everett and of Snohomish County. At the same time, this estuarine water body retains its high importance to diverse fish and invertebrate resources. Several species of economically valuable salmonid fishes use available aquatic habitats in Port Gardner and the lower Snohomish Estuary during their early marine life history.

Over the last century, the shorelines and benthic environments of Port Gardner and the lower Snohomish Estuary have changed with the colonization, industrialization, and urbanization of the Everett waterfront. We examined these changes from the perspective of their documented or inferred effects on use of the area by juvenile salmonids and on the quality of habitats available to these fish during their critical early marine life history. We assumed that fish behavior is driven, in part at least, by the principles of bioenergetics and optimal foraging strategy (e.g., Ollason, 1980; Puckett and Dill, 1985); these principles suggest that fish will respond to more stressful energetic conditions (less favorable current or temperature/salinity, poorer feeding conditions) by moving more rapidly until they find better conditions. Where conditions are more favorable energetically, fish will move less rapidly, increasing the time spent exploiting those areas.

APPROACH

Historic records of development along the Everett shoreline were researched through the archives of the Port of Everett (Port), the City of Everett (City), the Everett Public Library, Snohomish County, and the U.S. Army Corps of Engineers (COE) dating back to 1880. The effects of documented shoreline changes on the availability, functions, and values of nearshore habitats for juvenile salmonids were inferred based on a number of local studies, mostly unpublished, and on the wealth of information that has been developed over the last 25 years on the early marine life history and ecological sensitivities of juvenile salmonids in the region.

THE FIRST CENTURY (1880 TO 1980)

Industrial Development

In the late 19th century, industrial activities along the Everett waterfront and in the lower Snohomish Estuary began to significantly alter conditions encountered by migratory and resident fauna. In the early 1890s, log rafting began on the west side of Smith Island (Smith, 1977), and logging camps grew along the river and bay. The COE began to remove obstructions from Steamboat Slough, the most navigable natural waterway of the estuary, as early as 1883 (Dilgard and Riddle, 1973). This action led to accelerated erosion and subsequent siltation of the lower estuary and Port Gardner. The first steam sawmill was located south of the present South Terminal in the area now occupied by Harborview Park (Dilgard and Riddle, 1973). Wood products processing and export have remained as major industries in the Everett Harbor and waterfront areas.

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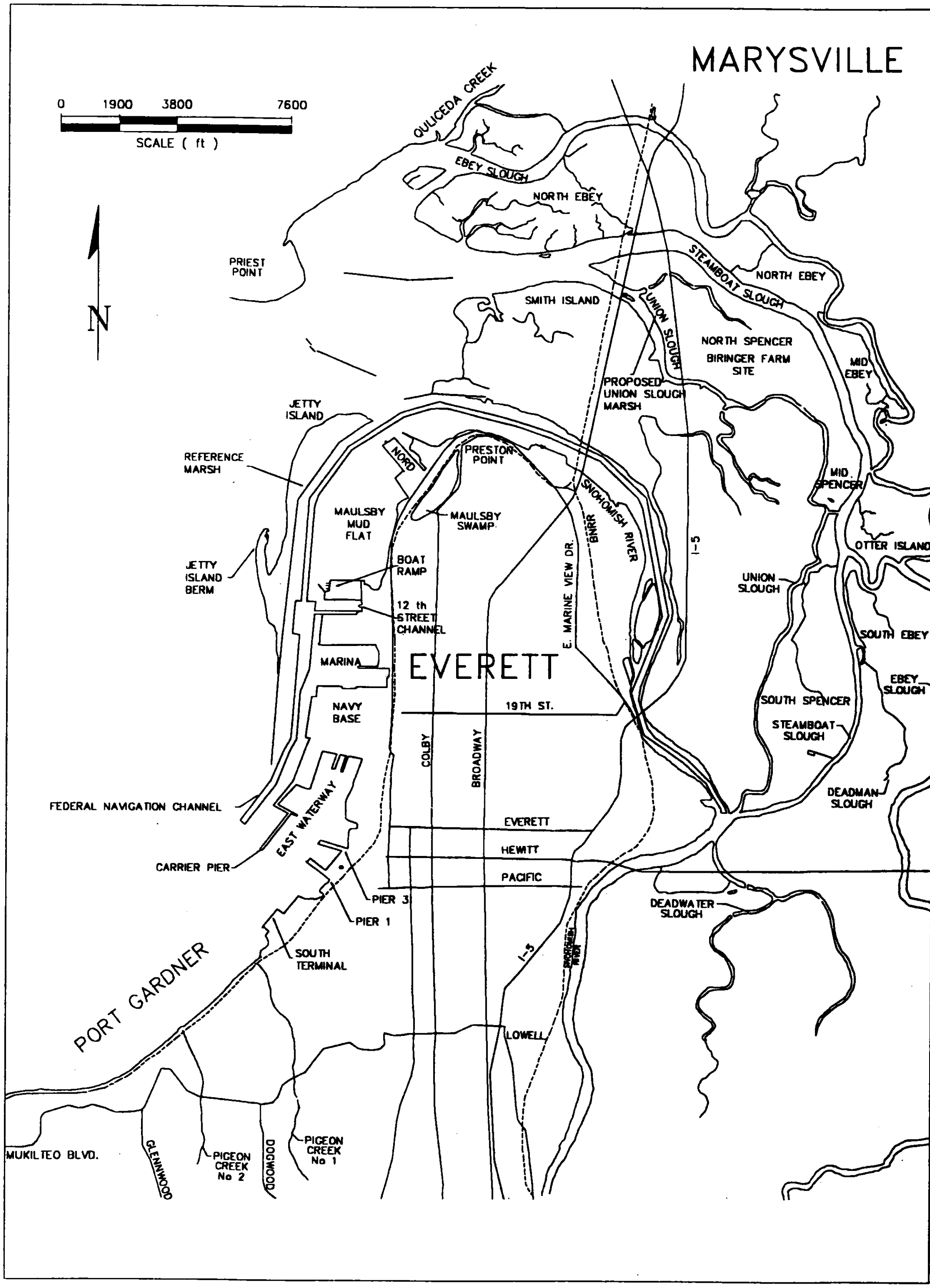

Figure 1. Port Gardner and the Lower Snohomish Estuary

The Great Northern Railroad was completed in 1891, mostly on fill along the upper intertidal zone between Everett and Mukilteo (Dilgard and Riddle, 1973); considerable waterfront development followed. Around 1895, work began on the training dike (the "jetty") that formed the present Jetty Island, and the harbor area was dredged around the turn of the century. River commerce rapidly adapted to log traffic, and harbor area log ponds proliferated.

Silting continued to be a problem and was exacerbated by flooding. Diking along the various distributary channels removed a large percentage of tidal marshes in the lower estuary and caused increasing amounts of sediment to reach the lower channels. Repeated maintenance dredging of the harbor and navigation channel was necessary to accommodate the lumber schooners and is still required. The navigation channel (Figure 1) was completed in 1903. The jetty was completed in 1905 to divert river flow and create a freshwater port in Port Gardner. Later a gap was cut in the dike to reduce the volume of water (and sediment) flowing into Port Gardner.

Waterfront industrial activities in Port Gardner during the first half of the century included sawmills, pulp mills, ship building and repair, log rafting and storage yards, petroleum distribution, and metals plating. Surface water discharges included five combined sewer overflows (CSOs), storm water outfalls, and many industrial discharges, including pulp mill wastes. By 1910, the Snohomish Channel along the Everett waterfront had about 44 lumber and/or shake mills. Many of these facilities were on pilings over the mudflats along the east shore, and much of the wood waste generated was dumped directly into the water. Numerous lines of closely spaced pilings and dredged channels crossed the flats to provide access and to contain the vast quantities of logs needed by the mills (Figure 2).

In 1931, the Port of Everett constructed the East Waterway, originally 8 feet deep and 100 feet wide. During the war years, the East Waterway was deepened, additional piers were constructed, the adjacent filled areas were expanded, and the waterway was intensively used as a naval base. Attendant activities of ship repair and fueling contributed contaminants to the sediments of the waterway.

After 1951, pulp mill waste discharges were treated or discharged to deeper water. Beginning in the 1950s, major new fills were placed at Hewitt Terminal, the Everett Marina, the 10th Street Boat Launch, and in 1976, Norton Terminal. All together, between 400 and 500 acres of mudflats were filled on the east side of the lower Snohomish Channel.

Effects on Juvenile Salmonid Habitat

These industrial activities altered the natural habitat in many ways, most of which are now perceived to have negatively affected ecological functions and productivity. Diking and filling removed shallow-water and tidal marsh habitat; vertical bulkheads and steep riprap altered remaining shorelines. These changes reduced invertebrate prey production for juvenile salmonids and possibly exposed them to greater risk of predation. Over-water structures and intensive log rafting across the mudflats adjacent to the river channel created mazes of pilings and fixed or floating obstructions to movements of animals, and shading and grounding of log rafts and floats reduced benthic productivity over large areas (Figure 1).

Chemical and wood waste, and perhaps thermal discharges from a variety of industries, including pulp and paper mills in the East Waterway and at South Terminal, reduced water quality in some areas. These discharges may have created chemical barriers to fish migration or even toxic conditions that on occasion led to fish kills. Clearly, habitat conditions during this period were much degraded from those of the natural estuary before the beginning of industrialization. One can readily theorize a loss of fitness—in response to the degraded conditions—in the populations of several species of salmonids using the estuary. Few data are available to document these effects, however.

One activity that in retrospect probably had more of a positive than a negative impact was the construction of the rock jetty along the lower Snohomish Channel downstream of Preston Point. This jetty probably stabilized shifting shoals of sand at the river's mouth and allowed formation of a large area of mudflats on its eastern (channel) side. These mudflats offset some of the reductions in mudflat productivity along the Everett waterfront. Subsequent disposal of dredged materials west of the jetty has led to the

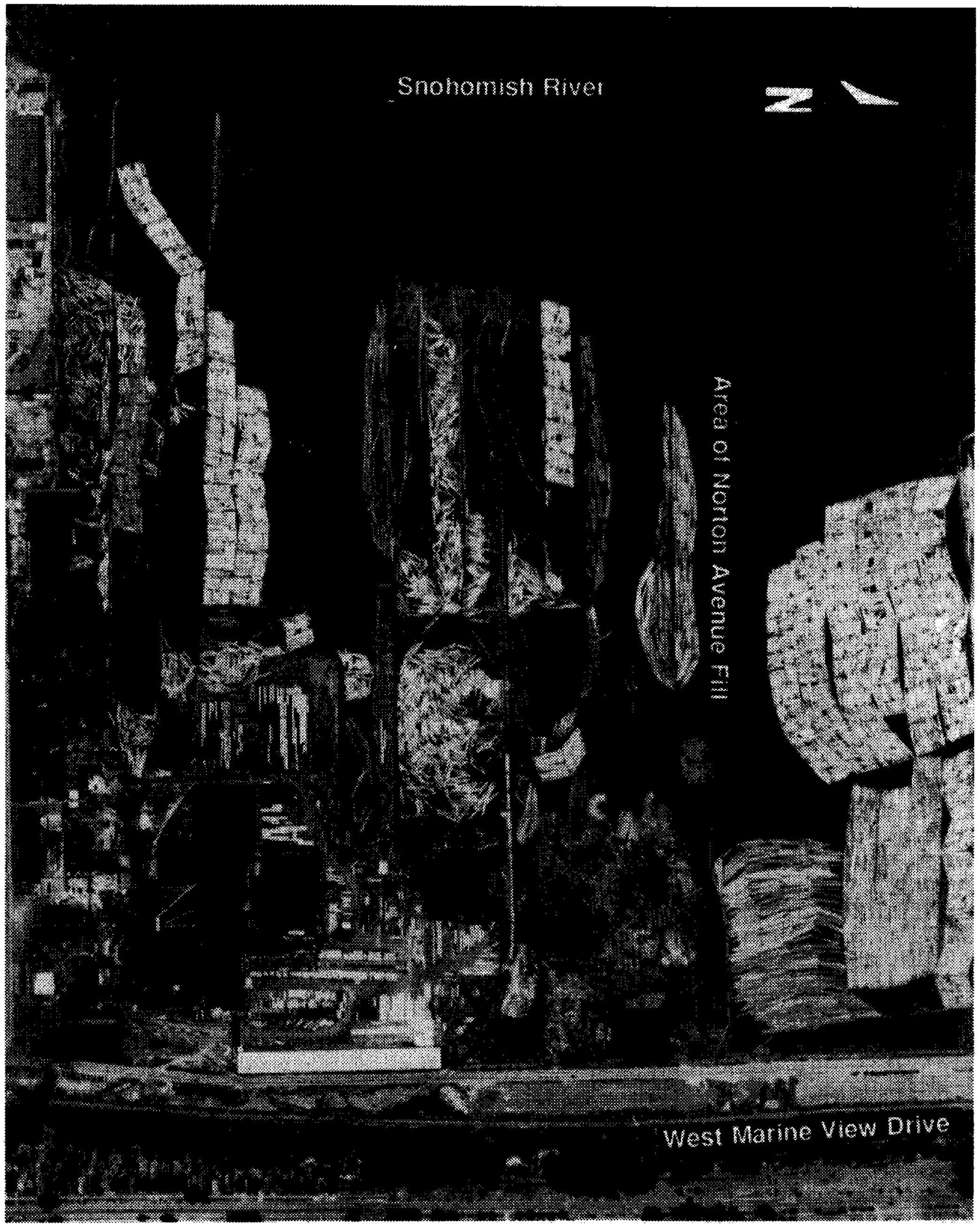

Figure 2. Aerial photograph of Everett waterfront in area of Norton Avenue fill, September 1946

formation of Jetty Island (Figure 1), which has become a unique ecological and recreational habitat in the city's harbor area.

During the 1940s and 1950s, at the height of development of the mills along the waterfront, juvenile salmonids following the shoreline downstream along the Everett side of the lower Snohomish River would still have encountered mudflats covered with log rafts and multiple lines of pilings stretching from the high tide line across the flats to the edge of the channel (Figure 2). In the East Waterway, much of the shoreline was vertically bulkheaded, and multiple wooden finger piers were present. It is very probable

that the 1940s and 1950s represented the worst of conditions for migrating juvenile salmonids. The new outfalls built in the 1950s moved the pulp mill effluents offshore. By the mid-1950s, the activity of the sawmills and shake mills was in decline.

Placement of fill in areas previously occupied by mills or used for log handling usually covered areas of contamination or wood waste and served to redefine and simplify the shoreline (Figure 3). Fish moving in shallow water along the shore now encounter a less complex series of obstructions and probably move more quickly through the area.

THE MODERN ERA (1980 TO 1995)

Industrial Development

With the Clean Water Act, the national Environmental Policy Act, and the State Environmental Policy Act, an era of environmental awareness began in the 1970s, and it continues to gain momentum with the state Sediment Management Standards (WAC 173-204). Permits for all waterfront projects now undergo intense scrutiny by resource and regulatory agencies as well as an informed public. Each new project is now viewed as an opportunity to improve habitat and restore natural functions. Any new impacts on aquatic or wetland habitat that cannot be avoided must now be mitigated. For example, the Port has terminated log raft storage on an area along the lower Snohomish Channel; increased benthic productivity will compensate for unavoidable losses due to projects constructed elsewhere.

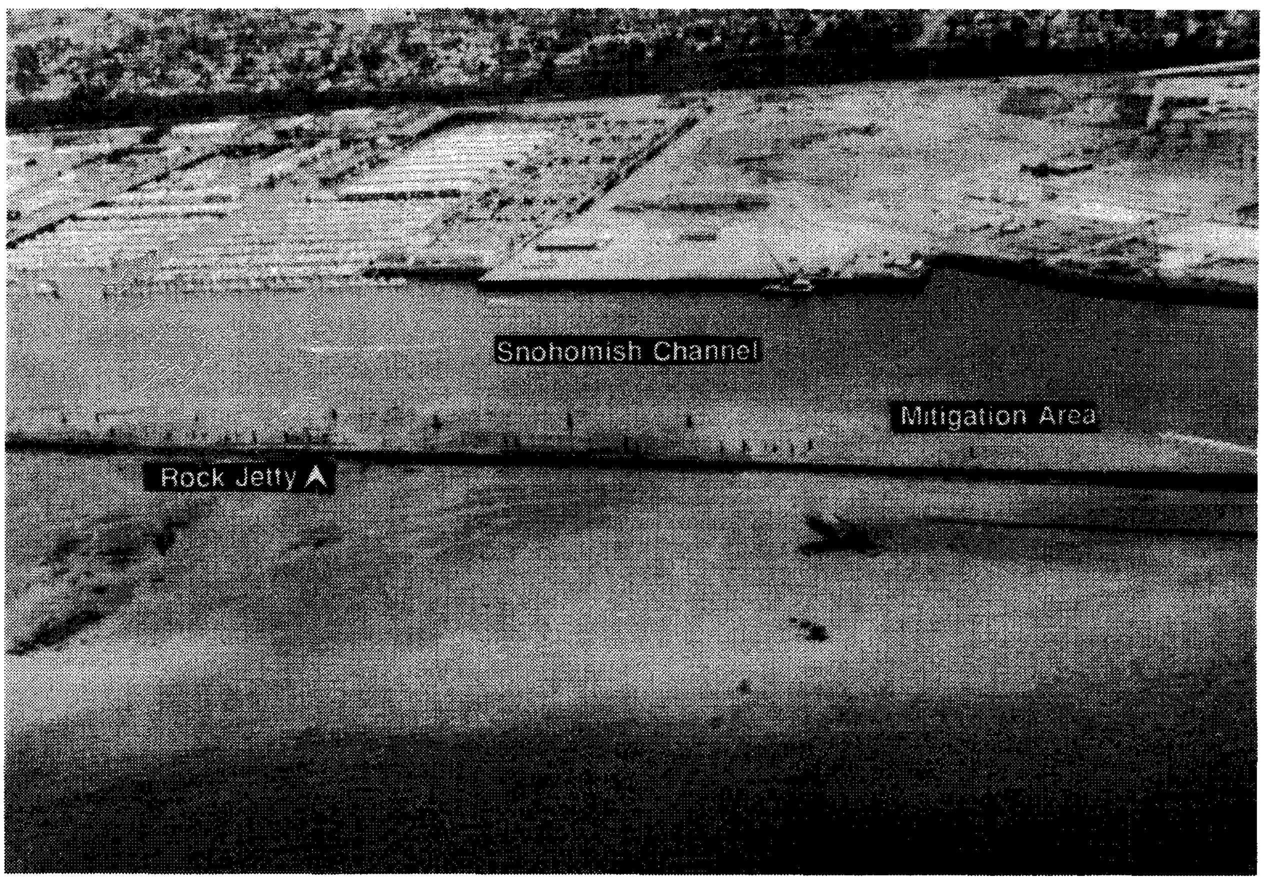

Figure 3. Aerial photograph of lower Snohomish Channel (1992) showing the Everett Marina (left) and Norton Terminal/Naval Station Everett (right)

Much-improved water quality regulation since the 1970s and a number of redevelopment activities in the 1980s and 1990s have tended to improve the quality of habitats along this shoreline migration corridor. There are no longer any surface effluent plumes; several finger piers have been removed; large stretches of shoreline at the head of the East Waterway have been cleaned of debris and surfaced with small riprap at moderate angles (2 or 2.5 horizontal to 1 vertical [2h:1v or 2.5h:1v]); some areas of contaminated sediments (e.g., Pier 3 north) have been remediated; and several other contaminated areas are scheduled for dredging in 1995. Log handling practices (bundling) and reduced log shipping have reduced the area covered by rafts and the amount of bark loss. Improved transfer facilities such as the Port's two log carriages and increased loading directly from the dock also have reduced the amount of bark lost to the water. These changes, plus source control measures implemented by the Port and the City, will maintain a healthier benthic environment.

Effects on Juvenile Salmonid Habitat

This discussion focuses on the probable manner of passage of juvenile anadromous fish through the lower Snohomish Estuary and Port Gardner and on ways in which the present habitat conditions affect the health and well-being (fitness) of those fish. Emphasis is placed on juvenile pink and chum salmon because they are considered the species most dependent on shallow-water shoreline habitat and are thus most at risk from habitat alterations such as have occurred in the area of concern over the last hundred years.

Lower Snohomish Estuary

The majority of the intertidal marshes that once lined all distributaries through the lower Snohomish Estuary remain diked (e.g., 74 percent loss reported by Bortleson et al., 1980). Juvenile salmon undoubtedly pass through this area more rapidly than they did before diking. Less access is available for feeding in rich tidal channels draining marshes, and less time is available to adjust to increasing salinities; both of these situations can be detrimental to smolt survival (e.g., Healey, 1982, 1991). The level of industrial activity, especially along the west side of the main channel, has diminished significantly with the closures of the Simpson and Weyerhaeuser pulp mills.

Studies in existing marshes and channels in the area, including an area that has naturally reverted to a brackish marsh following a mid-1970s dike break, have shown a moderate level of use by four species of juvenile salmon (Pentec, 1992a). Their data suggest that breaching of dikes will allow rapid return to conditions of biological productivity and value for juvenile salmonids as well as several other species.

Present conditions are far from those existing prior to industrialization but are probably better than they were before 1970. The number of marsh restoration projects planned in the area suggests continued improvement in conditions for downstream migrants. Remediation of the Tulalip Landfill Superfund site is expected to reduce a potentially significant chemical contamination source, although its present impact on salmon is uncertain. Only on the Smith Island side of the main river channel from Dagmar's Landing downstream is industrial activity maintaining levels of the 1950s and 1960s with new facilities in place or planned.

Port Gardner

Salmon smolts moving downstream along the Smith Island shoreline of the main Snohomish Channel encounter very favorable conditions as they pass the west end of the island (Figure 1). Beyond this point, the available habitats (saltmarsh, sandflats, mudflats, eelgrass beds), available food, and suite of predators are probably much like those that they would have encountered during the period before industrialization began. Conditions are probably better than they were during the first half of the century, when much more intensive log rafting was practiced, for example, on the flats west of Smith Island. The shorelines of Jetty Island, created during this century, provide extensive mud and sand flats that are intensively used by juvenile salmon and provide excellent prey and shallow-water escape corridors (e.g., Beauchamp, 1986; Pentec, 1991a, 1994). In 1989 and 1990, maintenance dredging provided material for creation of additional

shoreline, a shallow and productive mudflat, and a small salt marsh on the west side of the island (Houghton and Gilmour, this volume).

Larger smolts that may move down the center of the river channel likewise will not encounter unfavorable conditions. The navigation channel is deeper than the historic channel overall, but this should not influence these surface-oriented fish. The cessation or regulation of outfalls that were active and uncontrolled in the early part of the century has removed the threat of routine water quality problems. The primary risk faced by these fish is predation by birds, especially western grebes, that concentrate in the lower river each spring.

Smolts following the mainland side of the main river channel historically found broad mudflats stretching from Preston Point to near the Pigeon Creek No. 1 Delta. Fish moving downstream during low tide periods now find relatively narrow mud banks adjacent to the dredged channel or riprap protecting filled areas and extending to subtidal depths. Riprap angles are typically 2h:1v or less. At higher tides (e.g., > +1 ft mean lower low water), the broad mudflats at Preston Point, downstream of the Nord Door peninsula (the Maulsby mudflats), and in the 12th Street Channel become flooded. Some fish move onto these flats, apparently following shorelines. Many pink salmon, which are reluctant to sound under surface obstacles (Anderson, 1990; Feist, 1992) probably are led past the flats by the near-continuous line of floating boomsticks along the channel. During intensive sampling in the spring of 1994, Pentec (1994 unpublished data) found no salmon on the flooded flats except along the high tide shoreline, where numbers were occasionally large. Some fish do access the flats, perhaps through gaps in the boomsticks along the Maulsby mudflats; however, no salmon were taken in the center of the 12th Street flats, which were not protected by a boom. This suggests that the central areas of these flats are not widely used by juvenile salmon.

Diving surveys along the riprap at the Nord Door peninsula along with video and trawl surveys in the main channel and in the 12th Street Channel (Pentec, 1994, unpublished data) did not identify significant predators on juvenile salmon. Thus, the primary concerns for juvenile salmon in this part of Port Gardner are the availability of food and the risk of loss to avian predators. Pentec (1994 unpublished data) reported numerous great blue herons on the mudflats, which may account for the reluctance of juvenile salmon to remain in areas removed from the shoreline. Studies of epibenthic zooplankton (Pentec, 1991a) indicated a moderate to high availability on these flats. Thus, food is available across the full width of the flats, but only limited use of this resource by salmon occurs in the broad central region of the flats. Under present conditions, fish moving in over the flats would encounter fewer obstructions and much better habitat conditions than were present in the first half of the century, when log handling activities were much more intensive and large areas of the bottom were covered with thick layers of sawdust and wood debris.

Fish following the shoreline downstream today next encounter the Everett Marina (Figure 3). Floats along the channel likely divert many young salmon past the entrance to the marina in areas of relatively high current. Many juvenile salmon, however, do enter the marina; small schools of smolts have been seen in association with floats and pilings near the marina entrance by the senior author. These fish appeared to be feeding actively on small crustaceans associated with the epibiotal fouling community on the floats.

No data are available on the behavior of juvenile salmonids elsewhere in the marina. It is probable that they move along floats and moored vessels and, lacking a natural shoreline or cues from a strongly directional current, take a circuitous path back to the river. There are no data on the potential effects of passage through this marina on juvenile salmon, but data from other marinas suggest that marinas do not pose an undue risk for juvenile salmon (e.g., Cardwell et al., 1980). The Everett Marina supports some species, including larger sculpins, surf perch, and tom cod, that are potential predators on juvenile salmon (Pentec, 1991b). Once they leave the marina, juvenile salmon likely move rapidly along the riprapped shoreline of the former Norton Terminal fill (Figure 3), now the Naval Station Everett.

East Waterway

Several studies have demonstrated considerable use of shorelines in the East Waterway by juvenile salmon (e.g., Parametrix, 1985; Beauchamp, 1986; Feist, 1992; Pentec, 1992b). Precise movements are

unclear, but in general, smaller fish tend to follow the shoreline, while larger fish (e.g., coho and chinook, later season pinks and chums) are more dispersed offshore and around the ends of piers (e.g., Anderson, 1990). The smaller smolts that are still shoreline-oriented remain most vulnerable to habitat alterations.

During studies of the effects of pile driving on juvenile salmon movements, Feist (1992) documented that pink and chum smolts seemed to move freely past the new carrier pier and into the East Waterway. He also reported that these fish were very surface-oriented and appeared to linger in the vicinity of pilings or floating objects when not moving along the shoreline. The behavior of fish moving along a shoreline upon encountering a finger pier is variable; some fish appear to follow the pier line around the pier and into deeper water, and others follow the shoreline under the pier to the other side. It is presumed that the latter approach would carry less risk of predation losses than the path around the pier, especially where the shoreline is gradually sloped, providing a shallow-water refuge from predators.

Fish moving clockwise around the East Waterway in the 1940s to the 1960s encountered seven major finger piers and several lesser marginal wharfs and T-docks. All were constructed of densely spaced, creosote-treated timber piles. At the present, only two log piers remain, and there are three new concrete finger piers (including the new carrier pier). These new piers are supported by relatively few light gray concrete piles. Greater light penetration under these piers increases chances that migrating fish will choose to pass under the pier along the shoreline rather than taking the more dangerous route around the pier.

Construction of Naval Station Everett has resulted in the removal of old finger piers and the cleanup and redressing of the slopes of much of the west and north shorelines of the East Waterway. Newly placed small riprap in the middle to upper intertidal zones, although perhaps not especially productive, at least presents fewer risks to migrating salmon.

The eastern shore of the East Waterway presents the least hospitable environment in Port Gardner for migrating salmon. It is here that the economic tradeoffs of jobs (Scott Paper, Port of Everett) vs. salmon habitat are most evident. Much of this shoreline remains bulkheaded, and all of the deepwater terminal facilities except for the Navy's new carrier pier are located along this shoreline. Yet, even here there have been significant improvements in habitat conditions over those that existed 20 to 80 years ago, and more are planned.

As previously noted, chemical, thermal, and sawdust discharges directly to the nearshore waters have been eliminated. The old Pier 2 has been dismantled, and Piers 1 and 3 have been reconstructed of concrete. A portion of the shoreline north of Pier 3 has been riprapped on a 2h:1v slope, and a small pocket beach was created as mitigation for dredging the Pier 3 north berth. That dredging removed an area of chemically contaminated subtidal sediments. The Pier 1 reconstruction also straightened the shoreline under the pier to improve conditions for fish passage under the pier and replaced a small reach of bulkheaded shoreline with sloped riprap. Finally, new log handling practices, which result in low-velocity placement of log bundles in the water, and increased loading of logs across the dock (rather than from the water) have reduced the rates of bark loss to the water.

THE FUTURE

In the lower estuary, several projects to remove dikes and restore tidal wetlands are in various stages of implementation. Snohomish County, in cooperation with the Washington Department of Fish and Wildlife, is moving to restore of about 400 acres of freshwater wetlands on South Spencer Island (Frost, this volume). The Port of Everett has purchased about 400 acres of diked agricultural land on North Spencer Island and is planning marsh restoration projects as compensatory mitigation for unavoidable habitat losses from planned projects downstream. The City of Marysville has just broken dikes to restore about 13.5 acres of intertidal wetlands as mitigation for their new wastewater treatment plant (Ives and Matties, this volume). It is probable that 500 to 1,000 acres of diked lands will be restored in the next few years.

The Jetty Island berm project (Houghton and Gilmour, this volume) is expected to demonstrate a beneficial use of the large volume of dredged material that must be removed from the navigation channel. Similar projects may be implemented in the future as enhancement or for project-specific compensatory mitigation.

The Port of Everett is planning to construct a barge berth south of Pier 1 that would fill a small beach area but would have several mitigative benefits to overall habitat conditions in the area. About 1,500 ft of vertical bulkheads that now must be negotiated by shoreline-oriented fish would be replaced with sloped riprap; up to 90,000 cubic yards of contaminated sediments between Piers 1 and 3 and in the marina would be dredged up and placed in the nearshore fill. Mitigation, especially at a Spencer Island salt marsh restoration site, is proposed to replace lost habitat values for salmon, shorebirds, waterfowl, and Dungeness crab.

The present regulatory environment and "environmental awareness" dictate that shoreline conditions in the lower Snohomish Estuary and Port Gardner will only improve in the future. The recent revisions to the state Hydraulic Code emphasize that "no net loss" of fisheries habitat will be allowed. Several governmental initiatives and specific project plans are moving beyond mere preservation of the current, degraded status quo toward enhancement and non-compensatory restoration of habitats.

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THE RESPONSE OF ROCKY REEF FISHES TO HARVEST REFUGIA IN PUGET SOUND

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INTRODUCTION

In Puget Sound, a variety of demersal fish resources have been in depressed or declining states in recent years (Schmitt et al., 1994). The causes of the reduction in resources are not clear, but overfishing and habitat degradation are likely contributors. The use of marine harvest refugia or preserves where catch restrictions and habitat protection measures are fully or partially in place has become a popular idea to stabilize or increase fishery resources (Bohnsack, 1993; Roberts and Polunin, 1991; Carr and Reed, 1993). A variety of studies have shown that fish densities and sizes increase after the establishment of harvest refugia or are greater in comparison to the other harvested areas (as reviewed by Roberts and Polunin, 1991; Dugan and Davis, 1993). None of these studies has examined species living on temperate rocky reefs in the North Pacific Ocean.

The application of a refuge system has been discussed and partially implemented for several areas in Puget Sound, but studies have not been conducted to evaluate their efficacy. In 1990, five refugia were established in the San Juan Islands to protect marine fishes (except salmon) and invertebrates from recreational and commercial harvest. The oldest refuge is the Edmonds Underwater Park, which was established in 1970. All resource harvesting is forbidden at this park. The park includes a dry dock, which was sunk in 1935 (A. Olde, City of Edmonds, personal communication, 1993).

The Edmonds Park and one of the harvest refugia in the San Juans were included in a comparative study of lingcod (*Ophiodon elongatus*) and rockfish (*Sebastes*) density, size, and reproductive output among natural and artificial reefs in Puget Sound. Specifically, these variables were compared between harvested and refuge sites established at different times.

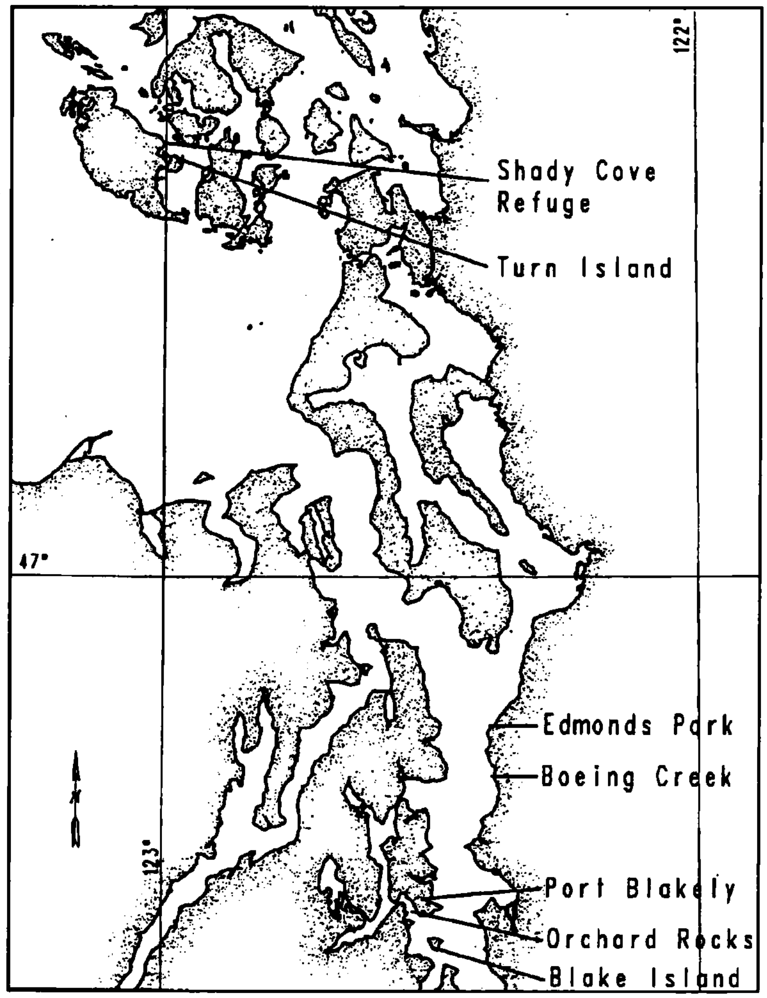

Figure 1. Northern and central Puget Sound study sites

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METHODS

Seven study sites including natural and artificial rocky reefs were surveyed for rockfish and lingcod abundance (Figure 1). Five sites were located in central Puget Sound. Four of these sites are open to fishing and were used by Matthews (1989), who evaluated the relative use of rocky reef habitats by rockfishes. These sites included the natural reefs at Orchard Rocks (OR) and Port Orchard (PB) and the artificial reefs at Boeing Creek (BC) and Blake Island (BI). The fifth site was the sunken dry dock at the Edmonds Underwater Park (EUP). In northern Puget Sound, two natural reefs were investigated. The east face of Turn Island is a fished reef composed of rocks and boulders. The refuge site at Shady Cove (SC) is located 2.7 km to the northwest and is just south of Point Caution along the east side of San Juan Island. The habitat at SC is composed of boulders and rocks.

Two scuba methods were used to obtain density estimates of reef fishes. A strip transect was used to estimate rockfish and lingcod densities at all seven study sites. A line transect method was used to estimate the density of lingcod and their nests at the two study sites in northern Puget Sound.

The strip transect method was similar to that used by Matthews (1989), who placed three fixed transect lines at each study site at approximately the 14 m depth contour (mean low, low water). Each transect line was 30 m long. Two divers swam on either side of the line and enumerated all rockfishes and lingcod within 1.5 m of either side of the line. Special care was taken to look into crevices with a light so sequestered fish could be counted. The divers coordinated their observations to prevent counting the same fish twice. All visible fish were included above the transect path, in contrast to Matthews, who only counted fish within 1 m of the bottom. Strip transects were conducted in two series at the central Puget Sound sites. All central Puget Sound sites were visited within a one-week period during September 1993 and then again during October 1994. In northern Puget Sound, the two sites were each surveyed 16 times during the spring seasons of 1993 and 1994. The surveys were paired so the sites were surveyed within several days of each other.

Line transects were conducted at the two sites in northern Puget Sound to estimate the density of lingcod and their nests. The method was adapted from LaRiviere (1981) and featured a permanent transect line 100 m in length set along the 14 m depth contour (mllw) at each site. One diver swam from the beginning of the line and stopped at 10-meter intervals. The other diver swam from the beginning of the line down and obliquely to a depth of 18 m (mllw). The diver then returned to meet the partner at the 10 m mark. This zig-zag process was repeated for each of the ten 10-meter intervals. During these transects all lingcod and any nests were enumerated and their approximate positions and depths recorded. At the end of the deep leg, the divers ascended to a depth of 5 m (mllw) and swam a straight 100 m path parallel and inshore of the deep leg. A total of 250 m was swum during the inshore and offshore legs. Lingcod and nest densities were estimated by the formula:

$$D=\frac{k}{ZL} \qquad 1)$$

where D is the density, k is the number of observed lingcod or nests, Z is half the measured visibility at 14 m depth, and L is the transect length. Each site was visited a total of 19 times, and SC and TI observations were paired within several days of each other during the winters, springs and summers of 1992, 1993, and 1994.

During any transect by either method, the divers estimated the size of each individual fish they observed. Sizes were estimated to the nearest 10 cm category, and size determinations were aided by a hand-held graduated staff.

The strip transect observations were used to estimate biomass and egg production per transect. The biomass of each observed copper and quillback rockfish and lingcod was estimated using length-weight regressions developed by Wildermuth (1983). These observations were then summed for each transect. Egg production per transect was estimated for copper rockfish (*S. caurinus*) and lingcod. The fecundity of

each observed individual was estimated using length-fecundity relationships determined by DeLacy et al. (1964) for copper rockfish and by Hart (1967) for lingcod. The eggs produced for each transect were calculated by summing the fecundity for each observed fish and dividing by half to compensate for an assumed equal ratio of males and females.

Strip transect data did not fit a normal distribution and were subsequently transformed with the square root transformation (Count'= (Count + 0.5)$^{1/2}$) for statistical analysis. Analysis of variance (ANOVA) techniques (Zar, 1984) were applied to strip transect data in order to test for density, size, biomass, and fecundity differences among sites and years. When differences were detected, the Tukey multiple range test was used to determine which treatments were different. Line transect data were compared using the Paired Differences T-test (PDTT) (Zar, 1984). For all statistical tests, null hypotheses were rejected at the 0.05 level of significance.

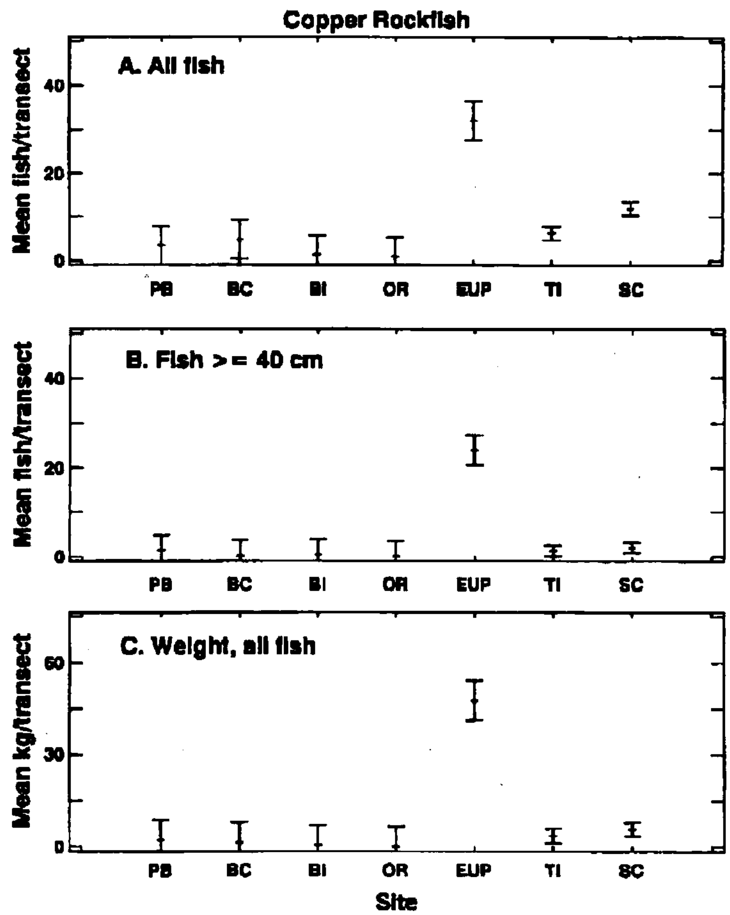

Figure 2. Mean fish densities (and 95% confidence limits) of copper rockfish at seven Puget Sound sites. A. All individuals, B. Individuals at least 40 cm in length, C. Biomass of all individuals.

RESULTS

Eighty dives were conducted to obtain density, size, and reproductive data at the central and northern Puget Sound sites. Thirty-eight dives were made to assess lingcod density in northern Puget Sound; 32 dives resulted in 96 strip transects in northern Puget Sound; and 10 dives resulted in 30 strip transects in central Puget Sound.

Strip Transects

Strip transect surveys provided data that revealed numbers, weights, and sizes of copper and quillback rockfishes and lingcod differed among the five sites in central Puget Sound (square-root transformed values, ANOVA). Multiple range comparisons revealed that the refuge at EUP had more or larger fishes than the four fished sites. There were more copper rockfish at EUP (mean 32.0 fish/90 m^2 transect) than at any of the four fished sites (mean 1.3-3.5/transect) (Figure 2). Copper rockfish measuring 40 cm or more were more common at EUP (mean 24 fish/transect) than at the four fished reefs (mean 0-1.5 fish/transect), and there was greater biomass of all copper rockfish at EUP (mean 47.7 kg/transect) than at the fished sites. For these three variables, the means estimated from the four fished sites were indistinguishable from each other.

In contrast to copper rockfish, quillback rockfish counts at BC (mean 46.5 fish/transect) differed from and were twice the mean count of the quillback rockfish at EUP (Figure 3). Mean counts from these two sites differed from the remaining three sites, which were indistinguishable from each other (mean 0-2.0 fish/transect). The EUP refuge had many more quillback rockfish measuring at least 40 cm (mean 9.5 fish/transect) than any of the fished sites (mean 0-0.5 fish/transect), and the biomass at EUP (15.7 kg/transect) was twice the biomass of quillback rockfish of BC.

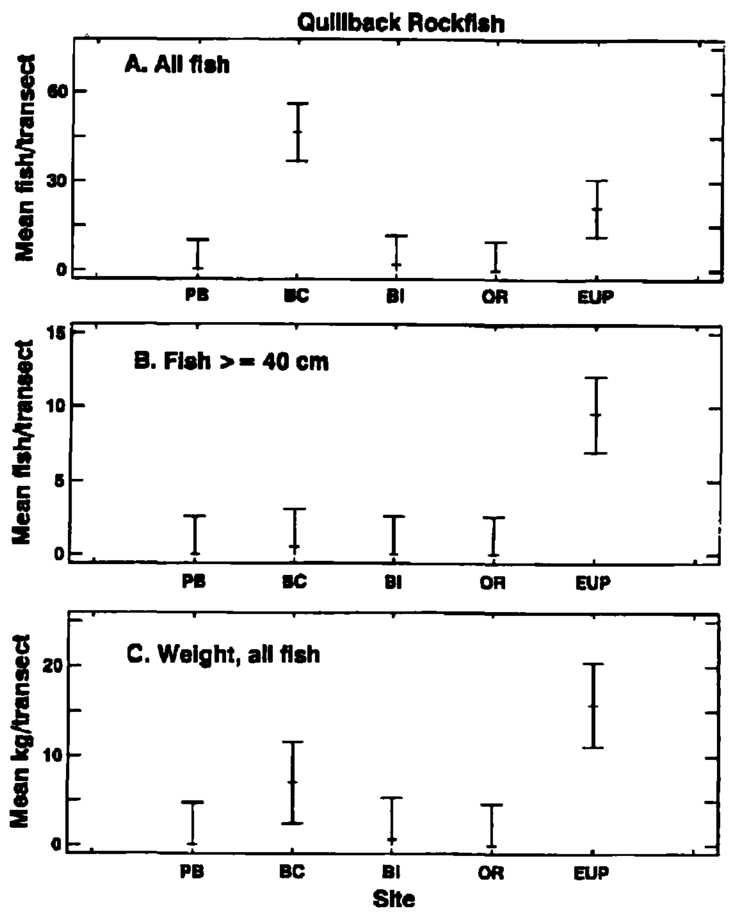

Figure 3. Mean fish densities (and 95% confidence limits) of quillback rockfish at seven Puget Sound sites A. All individuals, B. Individuals at least 40 cm in length, C. Biomass of all individuals.

Multiple range comparisons found that lingcod abundance was greatest at EUP (mean 3.3 fish/transect) but was indistinguishable from BC (mean 1.5 fish/transect) (Figure 4). Lingcod counts at BC were not different from those at PB, BI, and OR (mean 0.5-1.5 fish/transect). All the lingcod at EUP were at least 70 cm in length, while the other sites had either no large lingcod or very few (mean 0-0.3 fish/transect). Multiple range comparisons also revealed that lingcod were more massive at EUP (mean 38.2 kg/transect) than any other site, all of which were indistinguishable from each other (mean 1-2.8 kg/transect).

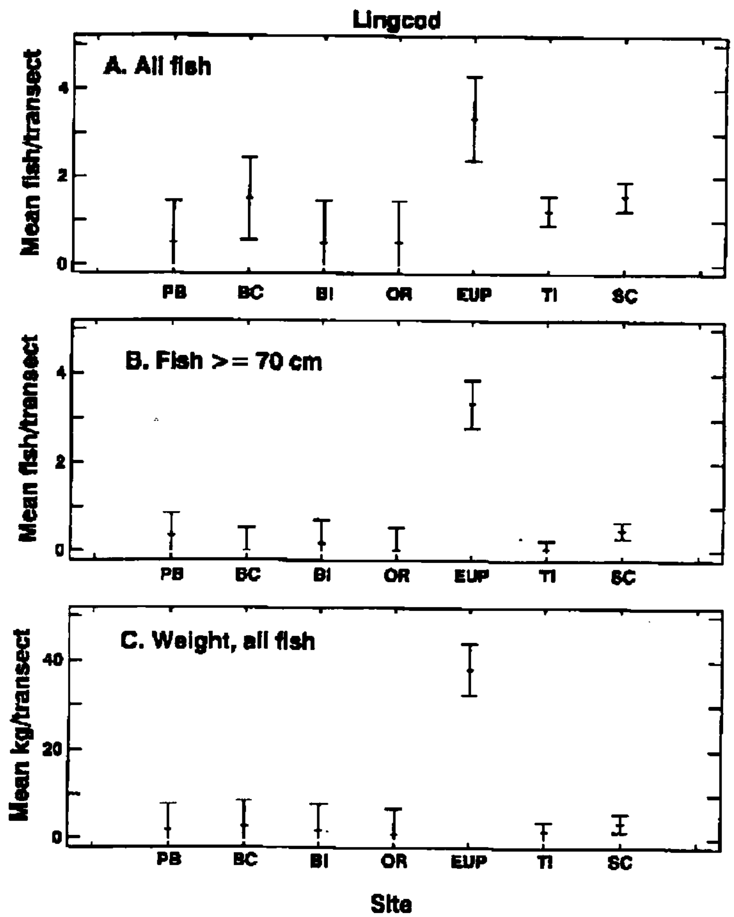

Figure 4. Mean fish densities (and 95% confidence limits) of lingcod at seven Puget Sound sites. A. All individuals, B. Individuals at least 70 cm in length, C. Biomass of all individuals.

The differences in mean counts, counts of large fish, or biomass per transect were not as great between the refuge and fished sites in northern Puget Sound as in central Puget Sound. SC only had twice the density of copper rockfish (mean 11.9 fish/transect vs. 6.3 fish/transect) than TI (square-root transformed values, ANOVA) (Figure 2). Analysis of variance of transformed data also found that SC had about twice the biomass of copper rockfish (mean 5.8 kg/transect) than TI (mean 3.7 kg/transect). The refuge had more copper rockfish greater than 40 cm (mean 1.9 fish/transect) than at TI (mean 1.3 fish/transect) (square-root transformed values, ANOVA). Quillback rockfish were not in sufficient abundance for statistical analysis at these two sites.

Lingcod were equally common at either of the two northern Puget Sound Sites (square-root transformed values, ANOVA) (Figure 4), but lingcod greater than 70 cm were more common at the refuge (mean 0.5 fish/transect) than at the fished site (mean 0.04 fish/transect) (square-root transformed values, ANOVA). Lingcod biomass differed by a factor of 2 (square-root transformed values, ANOVA) with the SC refuge having a mean of 3.6 kg/transect versus the TI fished site with 1.6 kg/transect.

Size differences

On average, the two refugia always had larger sizes of fishes that were either not observed in the five fished areas or were extremely rare (Figure 5). Copper rockfish measuring 50 cm were the most frequent fish observed in the refugia. In contrast, 30 cm individuals were the most common and largest size fish at the fished sites. Copper rockfish averaged 27.0 cm in length in the fished areas (n=364) and averaged 34.6 cm in the refugia (n=763). An average quillback rockfish measured 21.0 cm (n=294) in the fished areas, where 20 cm individuals were the most frequently observed size. Individuals measuring 40 cm or greater were the most common quillback rockfish observed in the refugia, while 40 cm fish were extremely infrequent elsewhere. In the refugia, quillback rockfish averaged 29.8 cm in length (n=127). The refugia most commonly contained lingcod that measured 100 cm or more, whereas the fished areas never had a lingcod exceeding 90 cm. Lingcod averaged 59.4 cm in the fished areas (n=77) and 77.7 cm in the refugia (n=95).

Line Transects for Lingcod

Lingcod densities based on line transect surveys were greater at the SC refuge (mean 160.0 fish/ha) than at the fished site at TI (90.9 fish/ha) (PDTT) (Table 1). While mean density of all fish differed by less than a factor of two, the mean density of fish measuring at least 70 cm at SC exceeded TI by a factor of three (PDTT).

Table 1. Mean densities (no./ha) and C.V.s obtained from line transects for lingcod in northern Puget Sound

Site	All Fish	Fish >=70cm	Nest
Turn Island (fished)			
mean	90.9	18.5	10.1
C.V.	11.2%	14.8%	32.5%
Shady Cove (refuge)			
mean	160.0	57.1	27.8
C.V.	6.4%	12.6%	17.0%

Reproductive Output

Calculated egg production for copper rockfish and lingcod was always greater in the refugia than at the fished sites (Figure 6) (square-root transformed values, ANOVA). Multiple range comparisons for central Puget Sound sites found that copper rockfish egg production did not differ among fished sites (mean 5,000 to 66,000 eggs/transect) but did differ from the EUP refuge (mean 7,600,000 eggs/transect). Lingcod egg production did not differ among the fished sites (mean 13,000-25,000 eggs/transect), but lingcod egg production at the refuge (mean 1,900,000/transect) was greater than at any fished site.

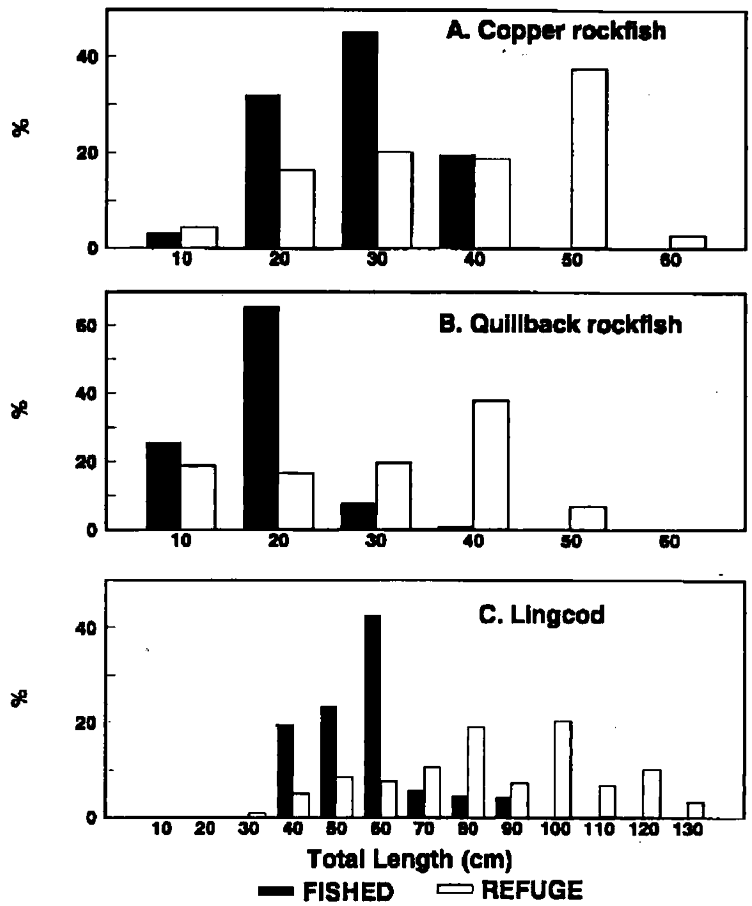

Figure 5. Mean length frequencies of copper and quillback rockfish and lingcod at fished and refuge study sites. A. Copper rockfish, B. Quillback rockfish, C. Lingcod.

Copper rockfish and lingcod egg production was much less in the northern Puget Sound refuge than in central Puget Sound but did differ by a factor of 2 between the SC refuge and the fished area at TI (Figure 6) (PDTT). The line transects for lingcod also revealed a difference in reproduction (Table 1): The SC nest density (27.8 nests/ha) was more than double the nest density at TI (10.1 nests/ha) (PDTT).

DISCUSSION

The site protected from harvest for 24 years showed dramatic differences in the abundance of large copper and quillback rockfish and lingcod compared to harvested areas in central Puget Sound. Copper rockfish density was six times greater in the Edmonds refuge than at the average fished site, and lingcod density in the refuge was twice as great as any fished site. Such responses of abundance and size to protection from harvest are within the same ranges as observed at other marine refugia around the world. Dugan and Davis (1993) found that refuge abundances of fishes and shellfishes were often two to 25 times greater than in surrounding harvested areas. The larger size categories of rockfish and lingcod observed at EUP were completely absent at the fished sites. Other studies of refugia have shown size increases in the absence of fishing. As early as two and one-half to four years after establishing refugia in Australia,

groupers were 13 cm larger (Beinssen, 1989; Ayling and Ayling, 1986). Other size-related increases have been observed in parrotfishes, butterflyfishes, and porgies (Roberts and Polunin, 1991), and Dugan and Davis (1993) found fishes were 12 percent to 200 percent larger in refugia than in harvested areas.

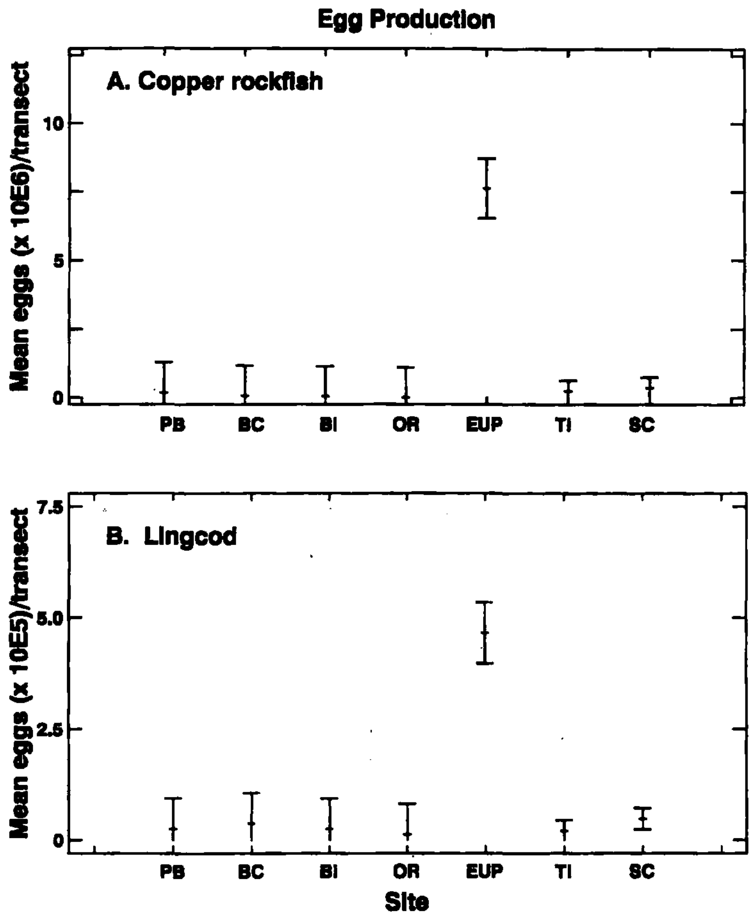

Figure 6. Mean egg production (and 95% confidence limits of copper rockfish and lingcod at seven Puget Sound study sites. A. Copper rockfish, B. Lingcod

The age of the refuge may be a factor explaining why the abundance and size differences were not as great in northern Puget Sound as in central Puget Sound. Copper rockfish densities differed only by a factor of two between SC and TI, compared to the six-fold difference between EUP and the other fished sites. The northern refuge was only four years old, compared to 24 years for EUP. Since rockfish grow slowly, mature late in life, and have low natural mortality rates (Leaman, 1991), the older refuge may have allowed abundance and size composition to recover to unfished conditions. In contrast to fishes in tropical and other temperate refugia (reviewed in Roberts and Polunin, 1991; Dugan and Davis, 1993), the slower growth of northern temperate fishes would necessitate long-term strategies for implementing harvest refugia.

Quillback rockfish densities at EUP were intermediate compared to the fished sites in central Puget Sound. Not all species always increase in abundance after protection. In at least three studies of refugia,

the abundances of some species did not differ after refugia were initiated or in comparison to similar fished areas (Buxton and Smale, 1989; Coyle et al., 1990; Bennett and Attwood, 1991). The lack of differences in these studies could be attributed to movement of species in and out of the refuge, age of the refuge, inadequate sampling, or differences in habitat. Similar factors could have affected quillback rockfish abundance; however, sampling was sufficient to detect differences among other species. Movements of this species is an unlikely cause since it has small home ranges and is sedentary (Mathews and Barker, 1983; Matthews, 1990). The higher densities at BC may be attributed to habitat differences favoring small fish or by the harvest of large quillback rockfish.

The observations made on the density, size, and reproductive variables in Puget Sound are influenced by the biases of the visual census technique (Brock, 1982). The rocky nature of north temperate reefs almost assures that fish, especially small ones sequestered in crevices, were underestimated. The densities estimated by this study should be considered minimum estimates of abundance, but the comparative inferences should remain valid if the biases are constant among the different study sites.

The four fished sites in central Puget Sound were those studied by Matthews (1989) but copper and quillback rockfish densities estimated in 1993-94 were two to 25 times lower than those for comparable months in 1986. Reasons for these differences could include differences among observers, change of transect positions, or actual declines in abundance. For most transects, we were certain of the line position because the original lines or buoys were still in place. Matthews (1989) was the only person counting a 3-meter-wide strip, whereas we used two observers to count the transect path. Higher fish counts would be expected by our increased observing effort. The difference in fish densities between studies is likely due to a decline in rockfish abundance over time.

The inference that refugia are more productive than fished sites is limited by the lack of replicate refugia, especially of long-established ones. Although the striking contrasts between the refuge at Edmonds strongly suggest fishing causes drastic changes in the size and density distributions of rockfish and lingcod populations, an alternative hypothesis is that the Edmonds refuge is simply more productive than other sites. The potential utility of refugia is, however, substantiated because differences were observed at the second refuge at Shady Cove. Tracking the progress of the northern Puget Sound refuge over time is warranted as well as a comprehensive program to monitor the effects of any refuge system.

The two refugia had much greater reproductive output than any of the fished sites. Copper rockfish in the northern refuge produced twice the eggs per unit area as the fished site, and two measures of reproductive output showed lingcod in the northern refuge outproduced those in the fished site by a factor of two. In central Puget Sound, the copper rockfish living at a fished site produced only 1 percent of the eggs per unit area as copper rockfish in the refuge. Lingcod living on the fished reefs of central Sound produced only 20 percent of the eggs produced by lingcod living in the refuge. If the population structure of the long-established refuge can be taken as an unfished (virgin) population, then the poor reproduction at the fished sites falls significantly below the "F35" guideline proposed by Clark (1991) and used to manage many groundfish fisheries on the West Coast of North America. Based on the differences in reproductive output, lingcod and copper rockfish populations in central Puget Sound may be stressed.

Few studies on the reproductive effects of no-harvest areas have been conducted. Only five of 31 studies reviewed by Dugan and Davis (1993) addressed the effects of refugia on reproduction, and these studies demonstrated only the effects on invertebrates. Goeden (1978, as cited in Roberts and Polunin, 1991) calculated egg production based on observations of density, size, and fecundity on a seabass and found that this species produced 80% more eggs per unit area in an Australian refuge than from nearby fished reefs. This result was similar to ours but is complicated by sex change with length for this species. Goeden (1978) also noted that the actual egg production in the refuge could be less than calculated because increased densities of large fish could result in competition for food or space thus reducing fecundity or frequency of spawning. Such effects may be possible in Puget Sound refugia, and closer investigation is required to demonstrate the egg production effect. Whether the egg production increases recruitment from Puget Sound refugia is unknown, but Doty et al. (in press, this volume) found the only significant area where young-of-the-year rockfish settled was on the east side of central Puget Sound. The Edmonds

Underwater Park was located in the center of distribution of the settlement, suggesting that EUP is a source of juvenile rockfish within and outside the refuge.

Carr and Reed (1993) discuss the goals and theoretical problems of designing and siting refugia which any policy on implementing harvest refugia should consider. Bohnsack (1993) suggests setting aside from 10 percent to 20 percent of marine habitat as harvest refugia. Although these studies do not provide definitive answers on refuge design, several nations have established pragmatic goals for integrating harvest refugia into fishery management. Australia and New Zealand have already established policies to set aside 10 percent of their coasts as harvest refugia (Dugan and Davis, 1993; Sobel, 1993).

Marine harvest refugia may enhance the production of recreationally or commercially important species. These benefits include increased abundance, increased age and size, increased reproductive output, enhancement of recruitment inside and outside the refugia, maintenance of genetic diversity, and enhanced fishery yields in adjacent fishing grounds (Dugan and Davis, 1993). Some of these benefits have now been documented for rocky reef fishes living in the existing harvest refugia of Puget Sound, but the driving factor for establishing other refugia should be increased fishery production, a factor that has not been documented for Puget Sound. Fishing in areas adjacent to refugia can increase catch rates (Alcala, 1988; Alcala and Russ, 1990), and Puget Sound anglers may similarly benefit from a system of harvest refugia.

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THE WDFW'S PUGET SOUND INTERTIDAL BAITFISH SPAWNING BEACH SURVEY PROJECT

Daniel E. Penttila[1]

INTRODUCTION

Marine beaches are a focus of human activity. An ever-increasing human population on Puget Sound endeavors to live near, play upon, and derive income from marine shorelines at an intensity, acre for acre, rivaled by few other regional habitat types. Intertidal beaches may also be, in terms of acreage, one of the most finite habitat types to be found in the Puget Sound basin. In the minds of most, the dominant biological resources of a typical beach on Puget Sound are shellfish, with a variety of harvestable molluscan species residing in and on the middle and lower zones.

Until recent years, intertidal beaches on Puget Sound might have been considered important to marine finfish only as transient feeding or refuge grounds. The one exception might have been the surf smelt, *Hypomesus*, which was known to deposit its eggs on upper intertidal beach material in a number of areas throughout the Puget Sound basin (Schaefer, 1936). Non-systematic surf smelt spawning habitat surveys undertaken by the Washington Department of Fisheries (WDF) during the 1972-1990 period commonly found significant extensions in the geographical distribution of known Puget Sound spawning beaches first mapped in the 1930s (Penttila, 1978; WDFW unpub. data). It was increasingly obvious that existing knowledge of these "critical" habitats, which WDFW was endeavoring to preserve through special consideration in the Washington Administrative Code (WAC) Hydraulic Rules, was quite incomplete. Within WAC baitfish spawning habitat protection procedures, consideration was to be given only to sites in the immediate vicinity of recorded occurrences of baitfish spawn *in situ*.

By 1990, however, it also became apparent that the surf smelt was not unique within the Puget Sound marine fish fauna for its upper intertidal spawning habitat requirements. The eggs of two additional marine fish species, the Pacific sand lance, *Ammodytes*, and the rock sole, *Lepidopsetta*, were also identified from similar sand-gravel upper intertidal beaches at a number of Puget Sound sites. Surf smelt, sand lance and rock sole were defined as the "target" species of the IBSBSP sampling effort.

From these observations evolved the idea of a more systematic, wide-ranging survey of potential habitat sites throughout the Puget Sound basin. The WDF Intertidal Baitfish Spawning Beach Survey Project (IBSBSP) was launched under the auspices of the Marine Habitat Investigations unit in 1991. With the disbanding of this unit in 1992, IBSBSP work was incorporated into the responsibilities of the Washington Department of Fish and Wildlife (WDFW) Baitfish Unit.

The goals of the IBSBSP remain: (1) a systematic survey of the intertidal shoreline of the greater Puget Sound basin sufficient to determine the distribution of the spawning areas and span of spawning seasons for the "target species" (surf smelt, sand lance and rock sole), and (2) development of a database on these resources for the use of fishery and habitat managers, researchers, planners, harvesters, and the general public. To our knowledge, no previous survey effort of this type, scale or purpose has ever been undertaken in the Puget Sound area.

METHODS

For IBSBSP planning purposes, the Puget Sound basin is divided into 22 survey sectors, generally with 50-80 lineal miles (80-129 km) of shoreline in each. Sampling is undertaken within seven or eight of these sectors over two consecutive years, after which survey effort is shifted to a new set of sectors. To broaden our geographical perspective, a biennium's survey sectors are not contiguous. During the course of the two

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survey years, an attempt is made to visit each sector four to eight times, with a goal of cumulatively positioning survey stations at about one-quarter mile (.4 km) intervals along all those shorelines with potential habitat for the target species, during their hypothetical local spawning seasons. A complete survey of the Puget Sound basin will be completed in such a manner in six to eight seasons with available staff.

About 50 IBSBSP surveys are undertaken annually. The most intense survey period is November-February, during which time all three primary target species are spawning in the Puget Sound area. Some survey effort also takes place during the summer months, when the spawning activity of several surf smelt stocks is at its peak. Surveys are generally undertaken by small boat, although some areas are routinely sampled on foot where there is a sufficient distribution of land access points to the shoreline.

Individual IBSBSP surveys generally consist of collecting data at 20-30 beach stations scattered along several miles of shoreline. To increase the resolution of the resultant spawning habitat maps, sampling sites have not been fixed. Rather, an effort is made to position sampling sites in different locations on each survey along a given shoreline. Surveys are generally undertaken during daytime low tides of +7 feet or lower (Seattle District).

IBSBSP beach sampling stations usually consist of the collection of a 5-6 kg pooled sample of beach surface material from 5 sites positioned at 20-foot (6 m) intervals along a 100-foot (30 m) length of shoreline. Tidal elevation of the substrate samples is constant within a station, but may vary among stations as the character of the distribution of the potential spawning substrate varies. Data collected at each sampling station include: location on a 7.5' USGS topographic chart, GPS latitude/longitude to .1 second, and code entries for upper beach texture, degree of human modification of the shoreline, sample transect distance from a tidal elevation landmark (usually the last high tide line windrow), qualitative visible density of spawn by species, width of potential smelt/sand lance spawning substrate zone, length of potential spawning habitat in the 1,000 feet (305 m) of shoreline centered on the station, and amount of direct overhead shading of the substrate zone.

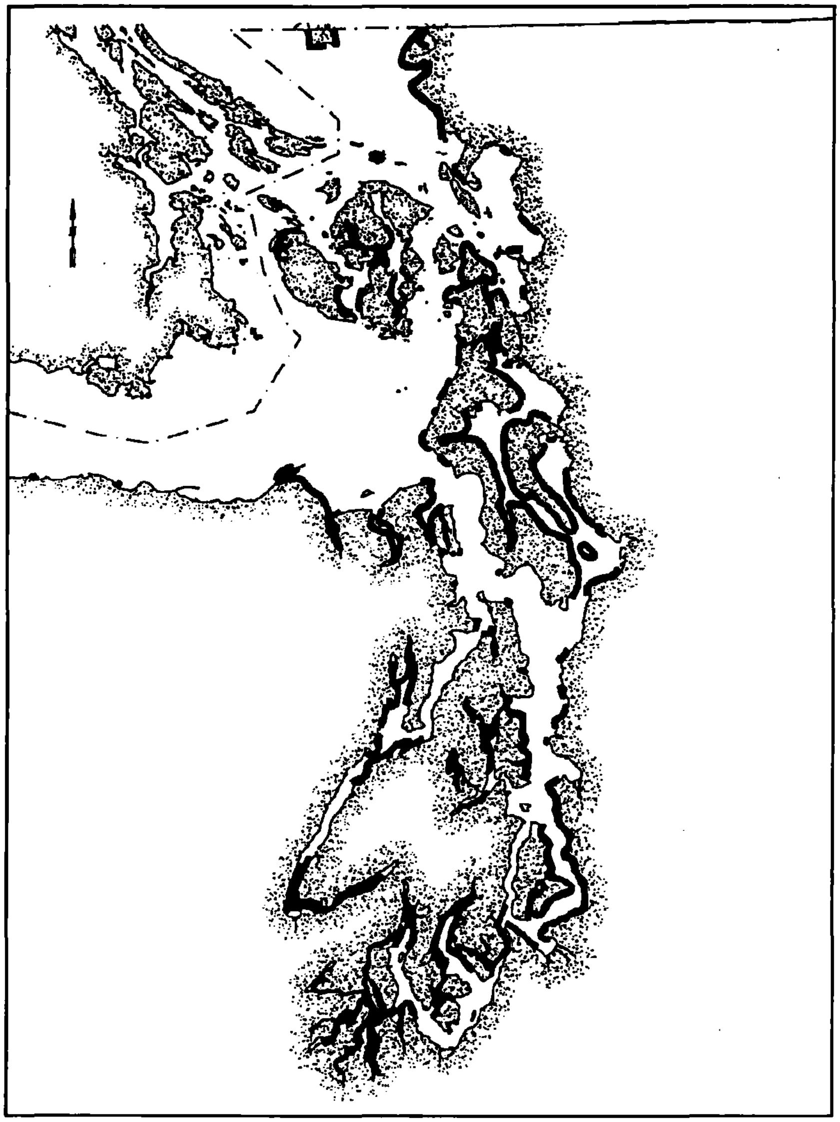

Figure 1. Puget Sound shorelines surveyed for intertidal baitfish spawning habitats by WDF Baitfish Unit, WDF Marine Habitat Investigations Unit, and WDFW Intertidal Baitfish Spawning Beach Survey Project, 1972-1994

When visible spawn deposits are encountered at a sampling station, several 100 g samples are collected from the deposit in lieu of the standard bulk sample. The deposit and its habitat context may be documented by photograph. In the case of fresh sand lance deposits, bulk samples of spawn-bearing beach material may be collected for grain-size analysis.

The standard bulk samples of beach material are wet-screened to recover that portion of the substrate material between .5 and 2mm in diameter. Any eggs of the target species, which are about 1mm in diameter, are presumed to be retained in this size-fraction as well. This material is then suspended, agitated, and "winnowed" in shallow water in a manner that concentrates the lightest material (including fish eggs) at the surface of the mixture, where it is skimmed off and preserved.

The preserved "winnowed light fractions" are examined at 10-15X. Any eggs present are identified, counted, and aged into a series of embryological developmental stage categories. For samples collected directly from visible spawn deposits in the field, a weight is also taken on the volume of material examined to accumulate the aged egg sample.

An IBSBSP database is being developed, using Paradox 3.5 software, for the management of the field and laboratory data. Summaries of all intertidal spawn/habitat observations, 1972-present, keyed to the latitude and longitude of any site in question, will be available upon completion. The IBSBSP-documented spawning ground distribution information is also to be incorporated into current WDFW GIS and "Priority Habitats/Species" databases.

Figure 2. Distribution of the known spawning beaches of the surf smelt, Hypomesus pretiosus, *in the Puget Sound basin*

RESULTS

As of October 1994, the IBSBSP survey coverage of Puget Sound shoreline was estimated to be about 40 percent completed (Figure 1). A total of about 3,900 beach sampling stations have been undertaken in the first three sampling years of the project (October 1991 through September 1994). Our supposition that surf smelt/sand lance/rock sole spawning habitat was more widespread in Puget Sound than previously thought has been borne out by the survey results thus far. Of all beach stations sampled during the course of the first three years of the project, about 34 percent have yielded spawn of at least one of the three target species. About 5 percent of the IBSBSP fall-winter beach stations have found eggs of two of the three target species co-occurring in the same beach substrate. When spawn is present in a typically dispersed condition, our processing techniques generally yield fewer than 50 eggs per bulk sample. At the present time, our criterion for official "documentation" of a spawning site for one of the target species requires that at least two of its identifiable eggs be recovered from the site on one occasion.

Before the advent of the IBSBSP in the fall of 1991, about 68 lineal statute miles (109 km) of surf smelt spawning beach were mapped in the Puget Sound basin (Schaefer, 1936; Penttila, 1978; WDF unpub. data). As of October 1994, that figure stood at 154 miles (248 km) (Figure 2). Documentation of additional "new" surf smelt spawning habitat has continued apace through the early part of the 1994-95 survey season. Significant extensions have also been made in the estimated spawning season for a number of local surf smelt stocks (Figure 3). Before the start of IBSBSP, year-round surf smelt spawning activity was known only for the San Juan Islands stock (WDFW unpub. data). At the present time, year-round spawning activity is known from several surf smelt spawning areas in the Puget Sound basin. As with the new findings for all the IBSBSP target species, it is presumed that our expansion of the known geographical range and seasons of Puget Sound surf smelt spawning activity does not represent any actual recent increase in those parameters, but rather is simply the result of the first extension of adequate sampling procedures into heretofore unexplored regions.

The increase in documented Pacific sand lance spawning beaches in Puget Sound as a result of the IBSBSP work has been even more dramatic. Five lineal statute miles (8 km) of beach were known to be used by spawning sand lance prior to the fall of 1991. That figure is now about 84 miles (135 km) (Figure 4). As with surf smelt, additional sand lance spawning sites are being documented with regularity during the ongoing 1994-95 survey season.

With the sampling of many new spawning sites and fresh sand lance spawn deposits, many elements of the local spawning ecology of this species are now better known. A summary of IBSBSP sand lance findings is presented in these Puget Sound Research '95 Conference Proceedings (see Session 8C, "Investigations of the Spawning Habitat of Puget Sound Sand Lance, *Ammodytes*").

As a result of the IBSBSP surveys, the documented spawning beaches for rock sole in Puget Sound have increased from about 3 lineal statute miles (5 km) to the 7 miles (11 km) known at present (Figure 5). Because upper intertidal rock sole spawning/spawn incubation activity was not previously reported in the literature, an egg identification study was undertaken with the cooperation of the Seattle Aquarium in early 1992. Several brood of wild-spawned eggs of the "rock sole" type were collected from beaches in southernmost Puget Sound and lab-cultured to hatching. The identification of the yolk-sac larvae was confirmed by researchers at NMFS (A. Matarese, NMFS/RACE, pers comm.).

Rock sole eggs have been recovered from upper intertidal beaches in Puget Sound from late December through March. We have found fresh, intact rock sole spawn patches, with 2-4-cell-stage eggs, clinging to upper beach surface material at several sites in southern Puget Sound during our investigations. However, documented intertidal rock sole spawn occurrences are largely confined to the region south of Seattle, and are relatively infrequent, compared to occurrences of surf smelt and sand lance spawn. The general abundance and widespread distribution of rock sole in Puget Sound might suggest that this species may not be an obligate intertidal spawner, as surf smelt and sand lance appear to be. They may be spawning in subtidal depths as well, although rock sole spawn had not been documented in the field in any habitat context prior to our initial observations of it in the Puget Sound intertidal zone (Garrison and Miller, 1982).

In addition to the three primary target species, the spawn of the Pacific herring, *Clupea*, is occasionally found on upper intertidal sand-gravel substrate samples in the Puget Sound region. Most commonly, these eggs are moribund and appear to have been detached from immediately adjacent marine vegetation substrates normally used by spawning herring. On a few occasions, herring spawning activity in the Port Susan area has been found to extend upbeach from the vegetated zone onto upper intertidal gravel, very much an exception to the general rule for spawning Puget Sound herring.

Upper intertidal beaches comprised of wave-motile sand and gravel are quite rigorous environments for organisms to attempt to inhabit. A relatively small number of species, including annelid worms, flatworms, gastropods, mites, isopods, and amphipods are found in such substrates with surf smelt, sand lance, or rocksole eggs. These co-occurring organisms tend to be more abundant and diverse in sheltered areas and on beaches with relatively large amounts or organic matter in the beach material.

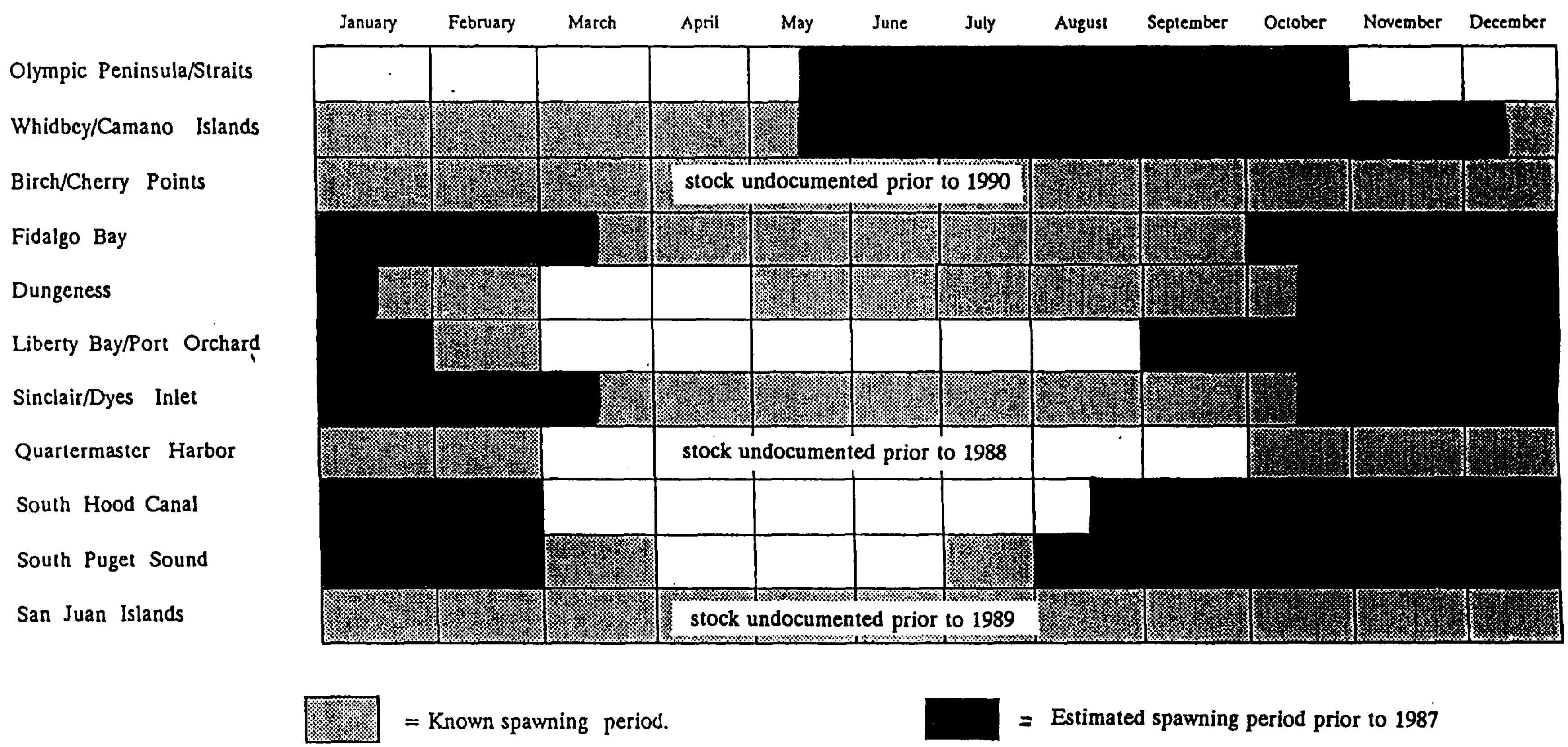

Figure 3. Seasonal occurrence of spawning activity in some surf smelt spawning areas in Washington state

DISCUSSION

The IBSBSP survey work has clearly demonstrated the existence within Puget Sound of a wide-ranging community of taxonomically unrelated species of marine fishes whose spawning behaviors have apparently evolved convergently to take advantage of sparsely settled and well aerated upper intertidal sand-gravel beaches for spawning purposes. Surf smelt, sand lance and rock sole spawn deposition and incubation must now be viewed as an integral biological feature and important ecological function of many of our local beaches, to be given consideration and appreciation along with the myriad of more visible and familiar elements of the Pacific Northwest's intertidal flora and fauna.

The goals of the IBSBSP and the nature of the target species' spawn and spawning behavior have required the development of new habitat survey techniques. Application of these techniques has allowed us to qualitatively detect the target species' spawn, and therefore document their critical spawning habitats and seasons, over broad areas at egg densities of the weight:volume equivalent of "parts per million." At the completion of this project, the total surf smelt, sand lance and rock sole spawning grounds in Puget Sound will undoubtedly be recognized as considerably more extensive than now known, given our current rates of documentation of "new" sites. Our present level of sampling effort, though clearly productive, cannot be considered exhaustive. The IBSBSP data will hopefully provide a moderately detailed record of the distribution of existing spawning habitats and seasons for the target species in the Puget Sound region, upon which detailed investigations can later be built.

Figure 4. Distribution of known spawning beaches of the Pacific sand lance, Ammodytes hexapterus, *in the Puget Sound basin*

The IBSBSP work has contributed to a more complete understanding of some of the important ecological functions of one of the more vulnerable and least-considered habitats within the intertidal zone. Lacking in clearly visible, "economically important" resources, upper intertidal sand-gravel beaches have commonly been sacrificed to bulkheading, filling, railroad construction, and other shoreline development activities, in man's effort to stabilize what will always be a dynamic system and to realize profit from it.

The public, including the typical shoreline landowner, seems generally unaware of the existence of surf smelt or sand lance spawning activity on local Puget Sound shorelines. In the past, much of the destruction of upper intertidal habitats that has occurred has likely been inadvertent, owing to this lack of knowledge for specific sites. In other instances, development proposals have been and will continue to be pursued with full knowledge of the potential for destructive impacts. We hope the documentation of widespread and frequent habitat use by these trophically and economically important resources will change attitudes in this regard. An enhanced spirit of stewardship of these important habitats must be fostered,

since a large proportion of them are likely to lie in private hands. Pragmatically, the extension of WAC Hydraulic Code protection to more documented marine fish spawning beaches in the Puget Sound basin has had an impact on the degree to which human development activities have been allowed to intrude into the Puget Sound intertidal zone.

The results of the IBSBSP work could also lead to a change in perspective regarding forage fish stock management in Puget Sound. Although comprehensive biomass estimates for local surf smelt and sand lance stocks are beyond the scope of the IBSBSP, it seems clear that these species may be more abundant and ecologically important to the Puget Sound marine ecosystem than previously thought. Although obviously present in great numbers in some local areas, surf smelt and sand lance tend to remain "invisible" to current hydroacoustic/trawl stock assessment techniques routinely and successfully used by WDFW to monitor Puget Sound herring stocks. These species, nevertheless, should be taken into account, along with the more familiar Pacific herring, in any considerations of total forage abundance or carrying capacity estimates of the local pelagic ecosystem. Ecological interactions between these species, as the adults partition the available pelagic habitat or the young mix in the many areas of Puget Sound where their spawning and nursery grounds co-occur, remain to be investigated.

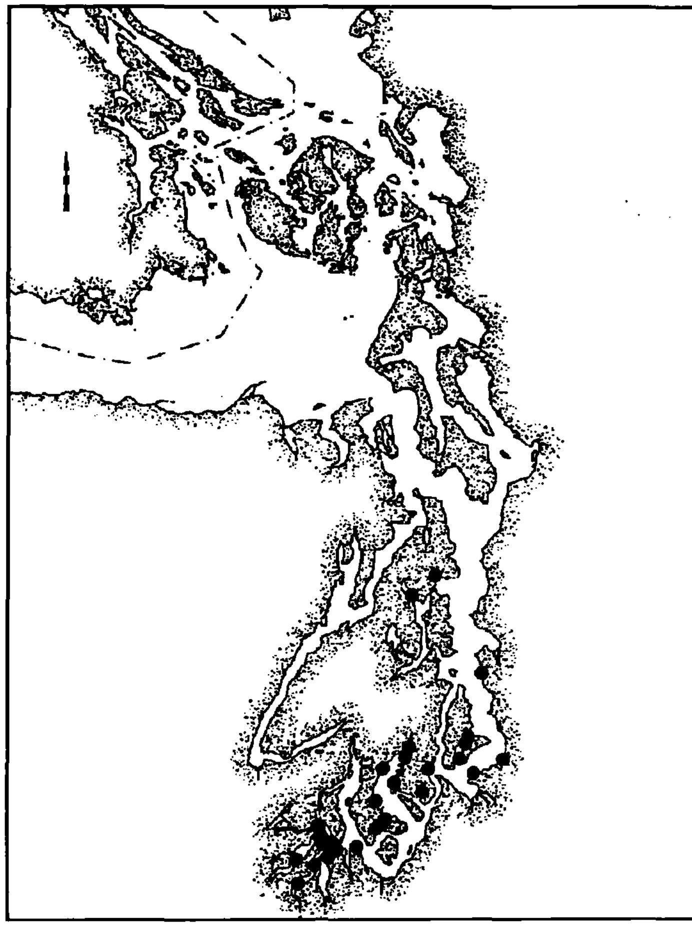

Figure 5. Distribution of known beach spawn sites of the rock sole, Lepidopsetta bilineata, *in the Puget Sound basin*

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PUGET SOUND RESEARCH '95

SESSION 2B

ASSESSMENT METHODS FOR INTEGRATED SOLUTIONS

Session Chair:

Thomas Mumford

Washington Department of Natural Resources

A META-DATA APPROACH TO INFORMATION MANAGEMENT IN THE GEORGIA BASIN

Thomas M. Fyles[1], Paul R. West[2] and Blair A. King[3]

In February 1970, the U.S. House of Representatives sponsored a blue-ribbon panel discussion on "The Management of Information and Knowledge." The keynote address was given by McGeorge Bundy, then president of the Ford Foundation (Bundy, 1970). His paper drew from experience with the first computerized databases and computational models for military and business applications in outlining the requirements for management of environmental information. He was particularly concerned with the public policy implications and emphasized "the direct relationship between the quality of raw data elements or inputs and the value of knowledge output" and the "distortions in judgment which will occur when non-quantifiable aspects are badly misjudged, or worse still, omitted entirely from the calculus." Among his several recommendations was the proposal that "data quality indices" be established to help the "executive decision maker to sift evidence, to discriminate between theories, to interrogate the scientist-scholar, to reach conclusions, and to help create the public support for needed action."

Since Mr. Bundy made his insightful comments in the dawn of the information era numerous sources have made explicit links between the "quality" of scientific information, the knowledge value of that information, and the credibility of the decision-making process based on that information. Indeed, in any sphere of activity, understanding product capabilities and limitations is essential for the effective use of the product. Most participants at this conference have a firm grasp of the environmental information they use, they understand its characteristics, and they successfully manage their personal information base. However, the overriding characteristic of modern environmental information is its quantity. This conference makes no exception. These proceedings attest to the diversity of scientific investigation of the Puget Sound environment, but by their very scale, the assimilation, appraisal, and application of the information presented lies beyond the capabilities of any one individual. The companion papers in this session examine aspects of information management as applied to specific and well-mandated activities. This paper begins from a more basic level, that of the nature of environmental information, to develop a framework for handling information in all its textures and complexities in a meaningful way. What we seek is a structure for information management that preserves the critical characteristics of the information in a scientifically rigorous form that is informative for all users, irrespective of their individual information needs (research, monitoring, modelling, regulatory, decision-making).

We begin by noting that environmental information is composed of two different aspects: environmental data, and environmental process knowledge (Cornford, 1993). Environmental data arises from measurements or observations of environmental variables and conditions—concentration of a contaminant in a particular medium, current/wave characteristics at a location, benthic community structure at a particular time. Data are inherently site-specific, and although sites in the Georgia Basin might share characteristics with other sites in other locations, the data will apply only to the particular location and time conditions of the measurement. Environmental process knowledge arises from the investigation of the dynamics of environmental variables. Process knowledge can be generated by controlled experiments, by analyses of sets of observation, by modelling, or by any other activity that establishes relationships between environmental observables. Process knowledge is expressed in theories, hypotheses, models, rules of thumb, conventional wisdom, or suspected correlations. Unlike data, process knowledge is not necessarily site-specific. Process knowledge from other geographic locations, such as the Baltic Sea or Long Island Sound, might well apply in the Georgia Basin.

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The management of environmental information thus involves two interrelated aspects: management of environmental data, and management of environmental process knowledge. Our strategy exploits the concept of "meta-data" as the central organizing principle. This paper develops management strategies for data, using meta-data, information appraisal, and a data information system as a demonstration vehicle for the power of this approach.

WHAT IS META-DATA?

Meta-data is "data about data" (Cornford, 1993). It is those characteristics of the primary data that provide insights into the nature of the measurements. It responds directly and completely to the Who? What? Where? When? Why? and How? questions posed at the outset by any user confronting a new piece of data. Meta-data is the essence of the data.

Consider a report of measurements of a suite of chlorinated phenolic compounds in samples of a flounder species. The meta-data for such a report would consist of the bibliographic information (Who?), the chemical constituents, the biological species sampled, and the media analyzed (What?), the geographical locations of the sampling (Where?), the sampling time and date (When?), and the sampling, storage, analysis, and quality assurance/quality control (QA/QC) methods used to generate the data (How?). The meta-data might also include summary information such as mean values, minimum and maximum, number of samples and number of samples above the detection limit.

The advantage of meta-data comes directly from a change in the scale of the information being manipulated. In lieu of a vast number of individual measurement values (primary data), only "data sets," or unified sets of measurements, are processed. The meta-data described below are easily handled on a (not very modern) personal computer even though they summarize many hundreds of thousands of measurements. The computational task has been dramatically simplified, but more important, the meta-data provide insights not readily available from the primary data themselves. Since the scale is larger, meta-data offer the potential to examine large-scale trends that are obscured by the smaller scale of individual studies. The meta-data offer direct access to cross-, inter- and multi-disciplinary analyses of regional monitoring and management significance. Even on its simplest level, the meta-data provide a useful resource for the communication of specialist information to non-specialist audiences and non-expert users.

Most important, the meta-data include indicators of data reliability or data "quality." In traditional scientific fields, quality control is "exercised informally by competent practitioners" (Ravetz, 1971). In most cases, the scientists doing the analysis have a good working understanding of the inherent strengths and limitations of their measurements and results. Other competent practitioners of the particular sub-discipline are also capable of reliably evaluating the applicability and information content of scientific results from their peers, but these assessments are not consistently or generally communicated. When the results of scientific research are used by scientists outside the sub-discipline, or as inputs to public policy decisions, the users of the information must either be knowledgeable in the details of the research methods or accept the results with no means of assessing their true utility. The latter situation usually prevails, with predictable limitations and consequences.

The assessment of scientific information is closely tied to issues that are widely recognized by the scientific community. QA/QC programs are widely practiced for many types of activities, including scientific investigation of the environment. The goal of these programs is "to ensure that the environmental data are scientifically credible by documenting adherence to proven scientific practices" (Clark, 1993). But even with a flawless QA/QC program in place, scientific uncertainty is inevitable due to the real variation in the population being sampled. Traditional statistical tools often assume the form of the population distribution without asking how well we know that distribution (Constanza, 1992). The credibility of scientific information then depends on a combination of these two aspects: How certain was the scientific measurement process? And how certain (or uncertain) is the result as a consequence of the inherent variation in the system under study? The communication of data reliability and applicability is thus a logical extension of the quality assurance process, which describes the extent of uncertainty in the information.

"Quality" is a tendentious word. In this paper we intend the focus to be on the reliability of the experimental outcomes, not on the skill, care, or attention applied within the fiscal, physical, or temporal constraints of the experimental program. Our perspective is consonant with the growth of indicators for environmental information, the establishment of SOE reporting, and the demands for harmonization among jurisdictions. We believe this new level of reporting and analysis is an imperative and urgent area for study and action and constitutes an opportunity for strengthening our understanding of natural systems.

Any system to communicate the reliability of the scientific information along with the information itself will ultimately serve more remote users of the information more than it serves the scientists themselves. It will place additional burdens on the scientists to generate the additional indicators, and it will expose the inherent uncertainties of the science to public scrutiny. Conversely, failure to communicate genuine uncertainty leads to simplistic interpretations and policy decisions that are justifiably criticized by the scientists who provide the basic information on which those decisions nominally are based. Communication of the strengths and limitations of the scientific information is the only way out of this impasse. It permits scientists to communicate effectively, albeit at some additional cost, and it gives non-expert users of scientific information access to the full range of insights science provides, yet tempers those insights with the inherent ambiguities. Scientists "should exhibit the structure of our uncertainty, so that the quality of our information in relation to its functions is assured" (Constanza, 1992).

INFORMATION APPRAISAL

"Assessing data quality is not glamorous, but it is highly desirable" (Roos, 1989).

The appraisal of information is widely practiced. In the bio-medical field, meta-analysis of the results of several similar studies is a common approach to evaluation of the efficacy of various procedures (Mann, 1990). In order to combine data from individual studies, an appraisal of each study is an essential prerequisite. The classification schemes are usually not particularly subtle, using categories of "good," "reasonable," "poor," and "bad" as one example (van Beresteyn, 1986). Similarly, meta-analyses in forestry (McCune, 1986), in ecology (Gurevitch, 1992), in institutional analysis (Roos, 1989), or in agricultural economics (Fletcher, 1991) all confront the same issues with descriptive scales to express the degree of reliability of the data.

In an organizational climate where defined experimental protocols have been developed, the reliability of information collected can be expressed in the degree to which the "right" methods were used. This circumstance occurs in multi-center biomedical studies with rigorous clinical protocols and in water quality programs with significant investment in protocol development. One example of the latter is the Puget Sound Water Quality Authority (PSEP, 1991).

The most comprehensive approach to data appraisal is found in the Arctic Data Compilation and Appraisal Program (ADCAP) of the Institute of Ocean Sciences (Sidney, B.C.), Fisheries and Oceans Canada. The program was later extended to include data for the West Coast region (WESCAP). Since 1979 these programs have produced catalogues to all types of physical, chemical, and biological oceanographic data. The compilations attempt to examine all data regardless of their source and status. Twenty-two catalogues have been published to date in the Canadian Data Report of Hydrography and Ocean Sciences No. 5 and 37 series, as volumes of the Arctic (ADCAP) and West Coast (WESCAP) Data Cataloguing and Appraisal Programs, respectively.

The ADCAP/WESCAP data appraisal efforts use a five-level scheme, or rating, to express the potential reliability of data (Cornford, 1982):

Rating	Data Reliability
0	Data are found to have errors. The data source contains obvious discrepancies.
1	Data are suspect because of recognized weaknesses that compromise the internal consistency of the data. Patterns or trends within the data are probably not real.

2 Insufficient information is provided to assess the reliability of the data set. Trends in the data may or may not be real.

3 Data are internally consistent. Patterns or trends within the data can be used with relative confidence. Comparisons with other data sets may be difficult or unachievable.

4 Data are internally consistent and are sufficiently standardized to permit comparison with other data sets of this rating.

This rating scheme is hierarchical to the extent that highest degrees of confidence in the data are classified as "4" or "3." However, "2" data are not necessarily technically inferior, as this classification simply reflects the documentation available to the appraiser.

An alternative approach to the appraisal and classification of scientific information is the NUSAP system (Funtowicz, 1991; Constanza, 1992). NUSAP stands for Numeral, Unit, Spread, and Pedigree, and was designed to describe the reliability of parameters such as the mean temperature rise due to a particular global warming model. A NUSAP notation for this value would be given as: a numeral value (3), a unit value (°C), a spread (± 50%), and a pedigree grade (0.5, on a 0-1 scale). The spread is just the statistical uncertainty in the result derived by conventional statistical techniques. The grade describes the pedigree of the model according to a matrix of qualitative characteristics of the theoretical, experimental, and societal contexts that produced the information. Cornford uses similar prose classifications to describe the degree of certainty in process knowledge (Cornford, 1993). High scores imply a sound theoretical framework based on substantive experimental validations and enjoying a wide degree of consensus support. Information from such a source is likely to have high predictive value and could be used with confidence in a variety of contexts. Lower scores imply a weaker theoretical framework, more anecdotal experimental explorations, or less consensus in the scientific community. The predictive capacity would also be lower, and the uncertainty in the information would be correctly communicated to the public policy forum in the lower pedigree score. In the example above (3 °C ±50% [0.5]) the pedigree of the model indicates a computational atmospheric model using indirect estimates, from one of several competing models.

The NUSAP grade expresses the uncertainty in a form that is amenable to an "arithmetic of uncertainty" (Constanza, 1992). More important, it provides a suggestive index rather than a defined mathematical quantity. The pedigree expresses the limits of a scientific field in which the process knowledge was generated as an assessment of the strength of the information.

The numerical rating of data "quality" as used by ADCAP/WESCAP, or the NUSAP scheme, are both effective ways to communicate scientific uncertainties to non-experts. They reflect a consensus approach to the doing and reporting of science. Unfortunately, any appraisal intended to classify data also involves personal judgment, presumably by an expert, but nonetheless potentially imprecise and subjective. To enforce objectivity on the assessor and hence ensure confidence in the assessments, the appraisal process requires well described protocols for the analysis of primary data. Our approach at the University of Victoria has been to formalize the appraisal process using "decision trees," a series of structured questions designed to yield a unique rating for each aspect of the measurement process (Fyles, 1993). The critical importance of systematic appraisal cannot be overemphasized.

For organic contaminants, five aspects of the measurement process were considered: sampling, storage, analysis, accuracy, and precision. Each aspect probes a different stage of the measurement process, and each seeks to classify the procedures at that stage. The overall rating is then assigned using the "weakest-link" principle: It can be no better than the lowest confidence step in the measurement process. Similar principles have been applied in the appraisal of benthic data, with four categories being appraised: collection, storage, analysis (if appropriate), and QA/QC (Johanson, 1994).

The decision trees developed do not seek to define the "right" method for a particular analysis. Nor are they a comprehensive "recipe book" that will deal with all eventualities. Rather they serve as a structure for working through an appraisal, as a source of information at various points in the appraisal, and as a framework for an evolving consensus on how best to accomplish various types of analyses. The

prospective or evolutionary aspect of the rating protocols and the process of analysis of meta-data, in improving and harmonizing ongoing experimental and field work, may be the most valuable aspects of the approach.

CODIS AND THE USE OF META-DATA

The practical implementation of the concepts enunciated above is the program CODIS (Continental and Oceanographic Data Information System) (Fyles, 1994). CODIS is an interactive data directory and index that searches, reports, and maps meta-data. It was designed to be compatible with the ADCAP and WESCAP data, it uses the same ratings system, and it contains the majority of the information contained in the 22 published catalogues. Moreover, two additional catalogues of data for the Fraser River Basin have been created: a catalogue of organic contaminants meta-data, and a catalogue of benthic invertebrate meta-data.

CODIS is principally designed to explore the use of meta-data in environmental data management. The data is structured to ensure that all searches of the meta-data will be "exact;" if meta-data exists within CODIS, every search will successfully retrieve all the available information. "Inexact" searches of text-strings are also possible, subject to the normal limitations due to variations in spelling and punctuation. The meta-data are geo-referenced (latitude and longitude of stations and transect lines, or polygons of survey areas). CODIS is implemented as an application of Microsoft Access for file management, search logic, and report generation. Mapping is handled by QUIKMap.

The meta-data in CODIS is classified within individual disciplines (Chemistry, Benthos, etc.) using controlled vocabulary lists with inherent hierarchy to simplify generalized searching. In the biological catalogues this includes a structured taxonomic classification with searches possible at different levels of generalization (phylum, class, order, genus, species). The measurements in the biological disciplines are grouped by similar types, for example, "Morphology," "Enumeration," or "Behavior." The corresponding chemical "taxonomy" groups similar constituents together as "parameters," for example "Hydrocarbons," or "Halogenated Organic Compounds." In the chemistry catalogue searches by "Parameter" and/or by individual chemical constituent are possible. The medium sampled is a meta-data search term in the chemistry catalogue as well. The meta-data in all disciplines include sampling dates, geographic locations, and data ratings as described above, so date, location, and data reliability delimited searches are possible.

An example will illustrate the types of manipulations possible and the potential of CODIS for data management. Our focus will be on the Fraser River estuary, and on organic contaminants in conjunction with benthic invertebrate populations. There are 548 data sets assigned in the chemistry catalogue for the Fraser River Basin; 295 contain information relating to the estuary. An "average" dataset in this catalogue involves nine chemical constituent analyses in a particular medium, from six stations, involving 15 individual samples for each constituent analyzed. Thus the catalogue represents some 40,000 individual samples from 1,770 locations in the Estuary. There is substantial duplication of location between data sets, so there are only 730 unique locations in the estuary. In the benthos catalogue, there are 168 data sets for the Fraser River Basin, including 96 associated with the estuary. The "average" data set has five different types of measurements, involving 16 species, at seven locations. Thus this catalogue represents some 7,700 measurements at 700 locations. Location duplication again reduces this to about 300 unique locations in the estuary.

In both catalogues, the majority of data sets are rated "2" indicating a lack of complete documentation available for the appraisal. The central question surrounding these data sets is whether this is just poorly documented but reliable science, or whether the poor documentation indicates real problems in the measurement process. We simply don't know. The appraisal protocols do reflect an ideal world, unconstrained by the fiscal and temporal realities experienced by most investigators. Moreover, many survey studies will attempt to cover more ground at the expense of time spent on statistical significance though QA/QC procedures, on the assumption that any problems suspected or uncovered will trigger a more rigorous examination at a later date. Even so, it is clear from all the meta-data appraisal work to date

that under-reporting is a significant and general problem. In-house "understanding" that is lost with time—the so-called "institutional memory effect"—is a related part of the same problem.

Whether the data reliability indicators are used will depend entirely on the hypothesis being tested. For some applications any type of information will be helpful. As an extreme example, any anecdotal historical observation of a crab population at a site where there now are none may serve to define an impact at a location. Conversely, some hypotheses require that the data be capable of supporting an analysis of trends.

As an example, consider an analysis of the interaction of chlorinated organic contaminants in water and sediment with benthic organisms. Bio-accumulation and effects on benthic populations were established in the '70s from observations at a variety of locations (Foehrenbach, 1971; Duke, 1970; Tagatz, 1982). To establish the extent to which a similar process is occurring in the Fraser River estuary, the meta-data need to be selected for "3" and "4" ratings only, as only these data sets will be sufficiently precise to support the required analysis.

A search in the CODIS benthos catalogue revealed that only 27 of the 96 data sets associated with the estuary were rated "3" or "4." Of those, only two data sets involved concurrent measurements of organic contaminants and benthic measurements: a survey report from 1972/73 (Albright, 1975), and a monitoring report from 1989 (Swain, 1989). Figure 1 shows the 10 stations involved as filled stars; the 1989 stations are all in Boundary Bay, while the 1972/73 stations occur in other parts of the estuary. The remaining 25 benthos data sets (Figure 1, filled circles, 41 stations) deal primarily with species identification, and with population and community structures measurements (density, enumeration). If there were concurrent information on water and sediment organochlorine concentrations, these data sets would also serve the purposes of the analysis. The open squares on Figure 1 show the 133 station locations of 53 data sets from the chemistry catalogue, all rated "3," and all containing sediment and water levels of organochlorines. A station-by-station inspection of the benthos stations for chemistry stations in close proximity (< 1 km), and close in time (< two years), reveals 31 of the 41 benthos stations can be supported by the chemistry data. The overlaps are distributed widely over the map area, and occur in roughly five-year intervals (1972, 1977, 1983/84, 1989).

This example illustrates the potential of meta-data to use an imperfect and fragmented historical record to provide a composite, multi-disciplinary picture. Clearly, if organisms were not analyzed in the past, no amount of modern manipulation will create data. Thus the data to examine bio-accumulation are simply not available apart from the two data sets with concurrent benthic and chemistry data. However, the analysis of the meta-data suggests that the historical data will support an analysis of ecosystem effects on benthic speciation, population, and community structure in the Fraser Basin estuary. The primary data still need to be analyzed in detail, using statistical tools appropriate for the diversity of the data represented. But the meta-data have greatly facilitated this task. The example has already identified the specific locations to be pooled, and has ensured that the primary data will support the trend-analysis required. The meta-data also provide bibliographic references. Alternative searches of the meta-data would provide even greater refinement, such as pooling by a specific measurement type, by a specific group of species, or within restricted time intervals.

For the context of this conference and session, the example provides a level of data organization that lends itself to the trans-boundary articulation of information on the contiguous coastal zone on the U.S. side. As noted in the introduction, the management of environmental information is a critical component in the management of the environment. The discussion has underlined the utility of structured data appraisal, of data reliability indicators, and of meta-data based information systems, to provide new tools for the manipulation and analysis of multidisciplinary environmental data.

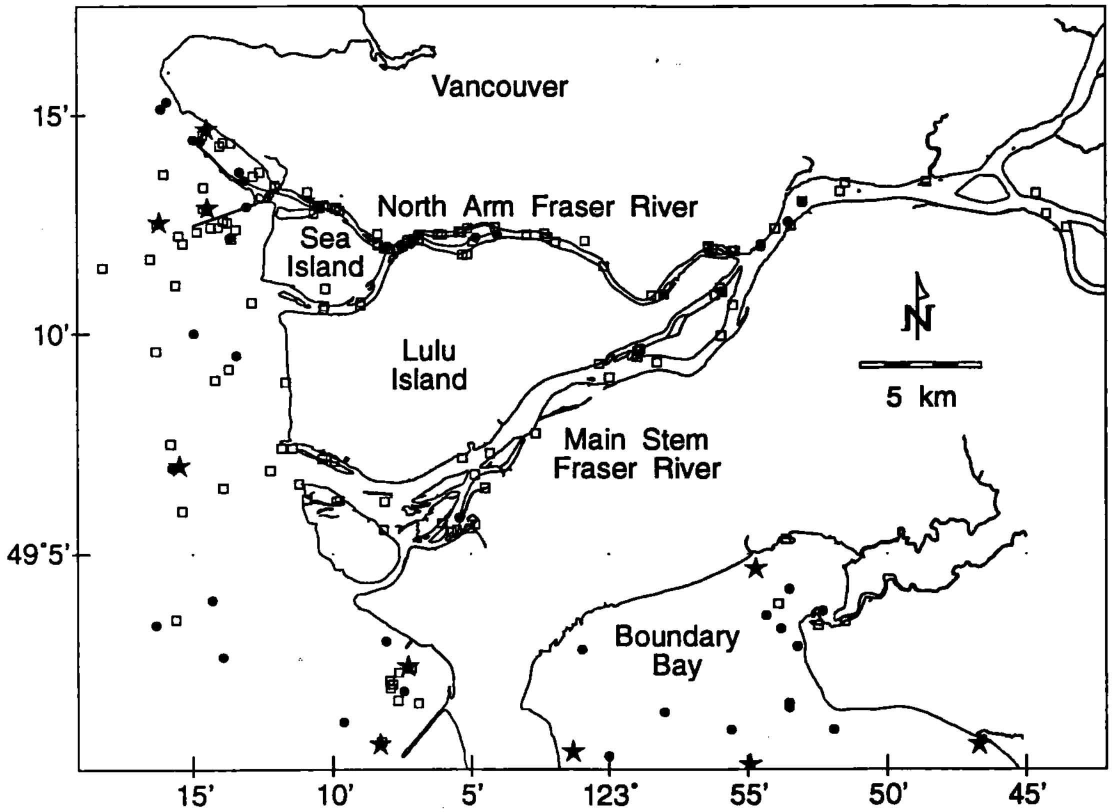

Figure 1. Geographic distribution of sampling locations in the Fraser River estuary rated "3" or "4." Filled stars: concurrent benthic and chlorinated organics data sets. Filled circles: benthic data sets lacking concurrent chemical information. Open squares: chemical data sets lacking concurrent benthic information.

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ECOLOGY'S WATER QUALITY PERMIT LIFE CYCLE SYSTEM (WPLCS): AN INFORMATION SYSTEM TO SUPPORT WATER QUALITY GOALS

Aaren Purcell[1], Roberta P. Feins[2] and Tim Hilliard[1]

INTRODUCTION

The Department of Ecology's Water Quality Program is charged with managing the quality of the waters of Washington state. The program issues, monitors, and enforces water quality permits through authority granted by state legislation and by the citizens of the state through the initiative process, as well as through authority delegated by the federal government. These permits allow and control the discharge of waste into surface waters and groundwater.

The Water Quality Program of the Department of Ecology has recently implemented a comprehensive computerized information system called the Water Quality Permit Life Cycle System (WPLCS, pronounced "wip-licks"). WPLCS is a permit information database, designed to manage information about water quality permits.

Information on water quality permits and water quality conditions is much in demand by other state and federal agencies, industries, interest groups and associations, researchers and the general public. This article describes what information is in WPLCS, how it is organized, how WPLCS contributes to the Water Quality Program's mandates and processes, and in what forms data can be obtained.

WPLCS HISTORY

The Water Quality Program's original computerized permit database (the Wastewater Discharge Information System or WDIS) was developed in 1984. In 1991, responding to the concerns raised by the Efficiency Commission, the Environmental Protection Agency (EPA), and other parties, the Water Quality Program determined to replace WDIS. A design for the new system was prepared in 1991. Phased development occurred from 1992 to 1994. Existing data in WDIS were converted to WPLCS in 1993, when an operational system was installed. While there is great potential for further enhancement of system capabilities, budget constraints make future development uncertain.

During WPLCS' development and growth, policy and priorities were set by an intra-agency steering committee, with substantial guidance from a users' group. Programming, fixing bugs, training users, and writing documentation was done by the Water Quality Program staff and several consultants (Executive Consulting Group for Phase I, and Environmental Information Consultants for Phase II).

The real power of WPLCS will emerge as the converted database is "populated" with correct, up-to-date data. Tracking down missing data and correcting outdated information in the database is a time-consuming task, and will continue for the next several years. Even more important is the development of procedures to ensure the quality and proper use of information from the moment it is generated until it is put to its final uses.

WPLCS COMPONENTS

WPLCS was the first Ecology database to be developed using state-of-the-art client-server database technology. Client-server technology allows data to be stored on a central, powerful computer (the server) and used by many individuals via their own computers (the clients) which are connected to the server via a network.

WPLCS server machines consist of personal computers with large hard disks running Oracle version 6.0 on a Novell network. The WPLCS database is stored and managed in Oracle software. WPLCS client

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machines consist of personal computers running MSDOS 5.0, Windows 3.1, and Oracle drivers. WPLCS data are accessible on the client machines from specially developed Oracle menus and forms used to add, edit, and delete information. WPLCS data can be retrieved using a set of customized menu-driven reports written in Microsoft Access. Programs written for Microsoft Excel allow data to be retrieved and formatted in spreadsheets.

Each Ecology regional office (Northwest, Southwest, Central, Eastern and the Industrial Section in Olympia) has installed a version of the WPLCS database that contains data for facilities and permits in the region. The regional databases are accessible to local staff via their computer Local Area Network; and accessible from other offices (and other agencies such as EPA) via the Ecology Wide Area Network. This arrangement allows data to be managed locally and to be combined to create state-wide reports.

Information from permit applications, permits, monitoring reports, and ongoing permit management activities make up the WPLCS database. The WPLCS coordinator in each region has primary responsibility for operation and maintenance of the database, while the WPLCS development staff maintain and enhance software. WPLCS coordinators are fully trained to use the system. They enter current data, catch up on backlogs of unentered data, correct older data, generate reports, and train other users. Permit managers—staff who track permit issuance and compliance—and managers are trained to use portions of the system to meet their information needs. A user's guide and various training materials are available.

WPLCS FUNCTIONS

WPLCS is the key to comprehensive administration of the state's discharge permit program, and is useful for:

- maintaining basic information on facilities;
- documenting permits, permit requirements and permit limits;
- tracking permit compliance;
- facilitating the process of issuing permits;
- analyzing patterns and trends in water quality;
- facilitating policy decisions;
- facilitating management decisions by reporting on the status of the Water Quality program; and
- producing materials to be used in communicating about the Water Quality Program to the rest of the world.

Basic Information on Facilities

Figure 1 sketches the elements of the WPLCS "world view" and their interrelationships.

A facility is a physical building or location that creates waste, including municipal sewage (e.g., by making paper, treating sewage, raising fish) whose disposal requires a federal or state permit. In 1994, WPLCS was expanded to manage data on facilities that generate stormwater.

WPLCS contains basic information about each facility: the current name, the mailing address, the physical location, the drainage basin (Water Resource Inventory Area) to which the facility discharges. More detailed information about processes (identified by Standard Industrial Code), composition of the waste stream, waste treatment, the effluent, ownership information, and information specific to certain types of facilities (e.g., number of dairy cows at the farm) is also stored. A facility may be currently active, inactive (e.g., shut down for renovation) or proposed. WPLCS maintains a history of facility status as well as name changes.

Basic facility information is currently complete and up to date in WPLCS; more detailed information is available for some facilities. A simple table produced from WPLCS data, summarizing basic locational data for some facilities, is shown in Table 1. Records of past changes in facility status or name are not

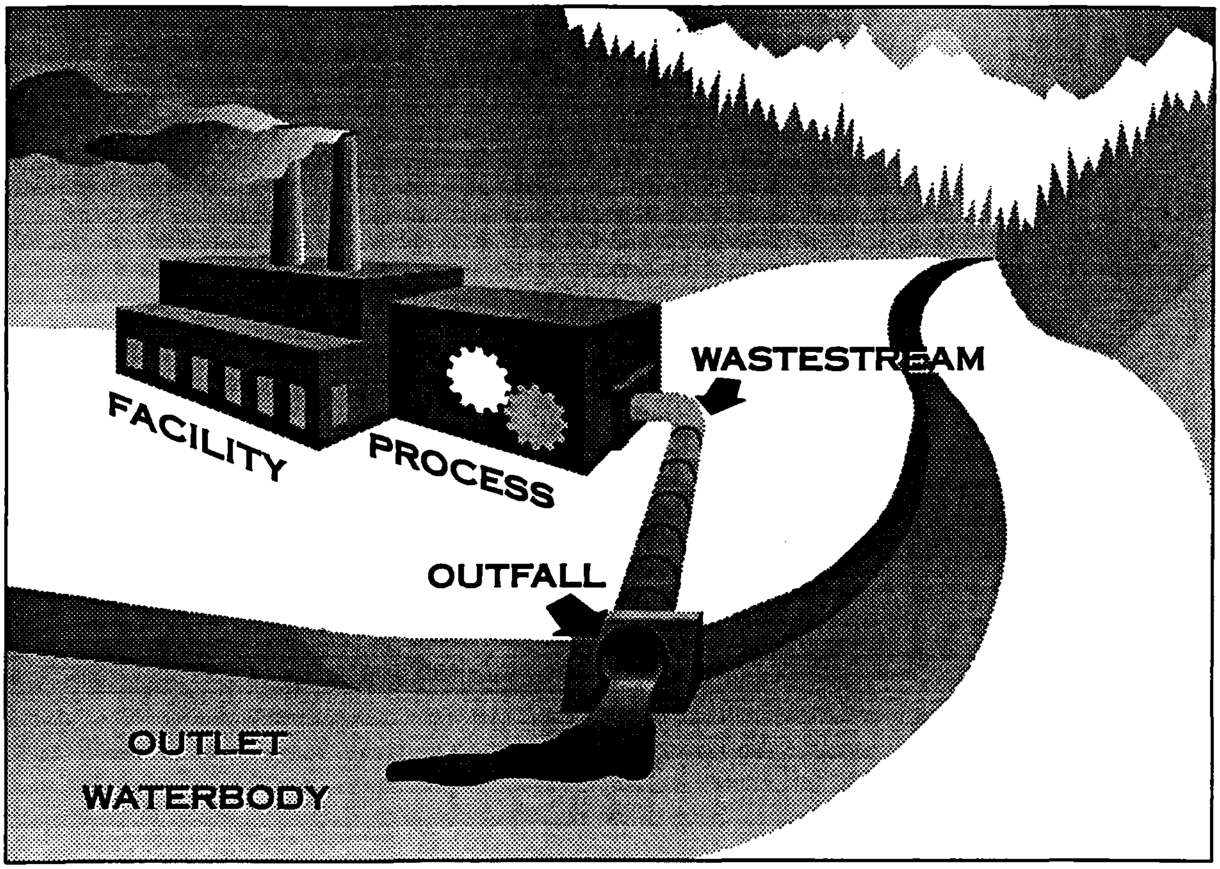

Figure 1. The world according to WPLCS

consistently available. WPLCS reports can list facilities by selected region, drainage basin, city, county, legislative district, facility type, size, and status.

Not every facility in the WPLCS database has a wastewater permit. Included are facilities that have been investigated and found not to require a permit, facilities whose permits have expired or have been canceled, inactive facilities that are not currently required to have a permit and facilities that are currently in the application process.

Documenting Permits, Permit Requirements and Permit Limits

Any facility wishing to discharge to waters of the state of Washington (including groundwater) must apply for and receive a permit from Ecology. WPLCS manages information on National Pollutant Discharge Elimination System (NPDES) permits (issued by Ecology under authority delegated from the federal government), state wastewater permits, stormwater permits and NPDES general water quality permits issued for classes of facilities (e.g., dairies, fruit packers). Table 1 shows WPLCS data on permits, summarized by permit type and status.

Table 1. Partial list of wastewater discharge permits in the northwest region (from WPLCS)

WAG030057A	2520 WESTLAKE BUILDING	Industrial	General	2520 WESTLAKE AVENUE N	SEATTLE	WA	98109
WA0030465B	AAA MONROE ROCK CORPORATION	Industrial	Minor	15421 166TH STREET SE	SNOHOMISH	WA	98290
ST0007343A	ADPRO LITHO INC	Industrial	St. to POTW	11012 MUKILTEO SPEEDWAY	MUKILTEO	WA	98275
WAG030001A	ALBERT JENSON & SONS INC	Industrial	General	880 TURN POINT ROAD	FRIDAY HARBOR	WA	98250
WA0020826B	ALDERWOOD WTP	Municipal	Minor	6400 PICNIC POINT ROAD	EDMONDS	WA	98020
WA0031402A	ALLIANT TECHSYSTEMS	Industrial	Minor	6500 HARBOUR HEIGHTS PKWY	MUKILTEO	WA	98275
WA0031275A	ALLSEASONS AQUAFARMS	Industrial	Minor	HWY 104	PORT GAMBLE	WA	98364
ST0007361A	ALPHA TECHNOLOGIES	Industrial	St. to POTW	3116 MERCER STREET	BELLINGHAM	WA	98225
WAG503041A	ALPINE ROCKERIES - MILLER QUARRY	Industrial	General	43530 SR 2	GOLD BAR	WA	
WAG030002A	AMERICAN MARINE CONTRACTORS INC	Industrial	General	3201 FAIRVIEW AVENUE E	SEATTLE	WA	98102
WAG030067A	ANACORTES MARINE MALL	Industrial	General	2900 T AVENUE UNIT C	ANACORTES	WA	98221
WA0020257C	ANACORTES STP	Municipal	Major	500 "T" AVENUE	ANACORTES	WA	98221
ST0007355A	ARCO - SERVICE STATION 6194	Industrial	St. to POTW	1672 STATE HWY 20	BURLINGTON	WA	
WA0022560B	ARLINGTON STP	Municipal	Minor	816 N WEST AVENUE	ARLINGTON	WA	98223
WAG133009B	ARLINGTON TROUT HATCHERY	Fish	General	17619 MCGOVERN ROAD	ARLINGTON	WA	98223
WAG030004A	ARNE LARSSON MARINE P/D-BOAT ST	Industrial	General	1005 NE BOAT STREET	SEATTLE	WA	98105
WAG030066A	ARNE LARSSON MARINE P/D-WESTLAKE	Industrial	General	2552 WESTLAKE AVENUE N	SEATTLE	WA	98109
ST0007265A	ARROWAC FISHERIES	Industrial	St. to POTW	207 HARRIS AVENUE	BELLINGHAM	WA	98225
ST0007316A	ARTISAN FINISHING SYSTEMS INC	Industrial	St. to POTW	14219 SMOKEY POINT BLVD	MARYSVILLE	WA	98270
WAG503058A	ASSOC S & G - ARLINGTON PIT	Industrial	General	23605 HWY 9 NE	ARLINGTON	WA	98223
WAG503053A	ASSOC S & G - BUTLER PIT	Industrial	General	1755 KELEHER ROAD	BURLINGTON	WA	98233
WAG503066A	ASSOC S & G - EVERETT PIT	Industrial	General	SEC 1,11,12 T 28N, R 4E, WM	EVERETT	WA	98203
WAG503052A	ASSOC S & G - HARBOR POINT	Industrial	General	3527 121ST ST SW	LYNNWOOD	WA	98037
WAG503084A	ASSOC S & G - SCHILINGER PIT	Industrial	General	HWY 3, MP 28 LOG YARD ROAD	BELFAIR	WA	98528
WAG030058A	B & J FIBERGLASS	Industrial	General	4905 GUIDE MERIDIAN	BELLINGHAM	WA	98226
WA0031437A	B P OIL \SITE #11093	Industrial	Minor	16320 MILL CREEK BLVD	SNOHOMISH	WA	98012
WA0020907C	BAINBRIDGE ISLAND, CITY OF	Municipal	Minor	1220 DONALD AVENUE	WINSLOW	WA	98110
ST0007364A	BAKER COMMODITIES	Industrial	St. to Ground	PO BOX 58368	SEATTLE	WA	98138
WAG133003A	BARNABY SLOUGH PONDS 1 & 2	Fish	General	3 MILES EAST OF ROCKPORT	ROCKPORT	WA	98283
WAG503106A	BEAVER LAKE QUARRY	Industrial	General	1450 BEAVER LAKE ROAD	MOUNT VERNON	WA	98273
WA0002143B	BELLINGHAM COLD STORAGE	Industrial	Minor	SQUALICUM FILL	BELLINGHAM	WA	98225
ST0007322B	BELLINGHAM FROZEN FOODS	Industrial	St. to POTW	PO BOX 1016	BELLINGHAM	WA	98225
WAG030006A	BELLINGHAM MARINE INDUSTRIES INC	Industrial	General	1001 C STREET	BELLINGHAM	WA	98225

WPLCS contains basic information about each permit: which facility is permitted, the date of permit issuance, expiration or cancellation, the name of the person who wrote the permit, the name of the person or company to whom the permit was issued, the contact person to call for more information. Each permit has a status: active (currently in force), canceled (no longer in force due to Ecology action), expired (no longer in force—past expiration date), extended (expired, but extended by Ecology) or temporary (in force, but not final permit conditions). WPLCS maintains a history of permits and changes in permit status, which is accurate for the last five years.

Basic permit information is currently complete and up to date in WPLCS. WPLCS reports can list permits by selected region, drainage basin, city, county, legislative district, facility type, size, and status, and permit type (NPDES, state and general) and status. It can list permits due to expire in a selected period of time (e.g., within two years from May 1995).

Permits limit the type and amount of certain materials in the discharge. There are simple permit limits (e.g., "Chlorine must not exceed 250 milligrams per liter at any time") and more complex seasonal or contingent limits (e.g., "The pH of the effluent in pipe 2 is restricted to a range between 6.8 and 7.4 during the months of April, May and October"). Permit limits can be set in the permit, or imposed by an enforcement order. Limits may become inactive over time, or due to an appeal of the limit by the regulated facility. Permit limits are entered into WPLCS, and their status (active or inactive) can be tracked.

Permit limit information is currently complete and up to date in WPLCS. WPLCS reports can list permit limits by selected region, drainage basin, facility, or facility type. Programs allow permit limits to be transferred to a spreadsheet.

In addition to permit limits, permits often contain reporting requirements, known to WPLCS as compliance submittals. Usually, the facility is required to submit a monthly or quarterly discharge monitoring report. The permit specifies which chemicals or conditions must be reported (e.g., "a weekly average of Biological Oxygen demand must be reported for Pipe 2 at the outfall"). Other types of compliance submittals may include one-time characterization reports and sludge management reports.

Data on discharge monitoring requirements is currently complete and up to date in WPLCS. Special WPLCS reports allow a user to prepare blank state and EPA monitoring forms customized to the monitoring requirements and permit limits of a particular facility. These forms are most often sent to the facility for their use in submitting monitoring data. A total quality management workgroup is currently looking into reducing duplication of effort by allowing for electronic transfer of data from facilities to Ecology and EPA. Improving and ensuring the quality of monitoring data is their main concern.

Tracking Compliance with Monitoring Requirements and Permit Limits

On the basis of data provided in the various compliance submittals and data from inspections, WPLCS can help permit managers answer these questions: Is the facility in compliance with effluent limitations specified in its permit? Has the testing schedule been met? Have the reporting requirements been met?

During the life of the permit, monitoring data and other required submittals are received from the facility and logged into WPLCS. Staff decide whether the submittal itself (form, content) is in compliance with the terms of the permit; WPLCS can produce a list of received, missing or non-compliant submittals, as well as pending submittals with their due dates.

When discharge monitoring reports are received, they are logged as submittals and their data are entered into the WPLCS database. Results reported in the compliance submittal are compared with the content and frequency requirements specified in the permit to see whether the submittal is complete. Data are also compared to discharge limits to see whether any violations have occurred. The database uses the current date and the permit limits to flag data that appear to be permit violations; final determination of a violation is up to permit managers.

At least one year's worth of discharge monitoring data is available in WPLCS; records for some facilities and parameters go back to 1986, and new data are being added as received. The data can be expressed as a graph, as a spreadsheet, or in raw form as a list or list of violations.

Ecology staff also determine permit compliance by inspecting facilities. WPLCS stores basic information on the dates and personnel of an inspection, inspection type (e.g., sampling or non-sampling inspection), sampling data collected during an inspection, and lists of follow-up actions that should be taken, either by Ecology or by the facility, in response to inspection findings.

WPLCS can track enforcement actions taken by Ecology in response to violations of various kinds: failure to apply for a permit, failure to submit a required report, exceedance of a permit limit. Ecology actions can range from informal letters to formal orders or notices; WPLCS can track the history of a single enforcement action through responses and appeals, and also provide enforcement histories for a facility.

Generalized inspection information is available for the last year. Enforcement data is not yet available in WPLCS; the Ecology Central Programs Enforcement Database contains correct and up-to-date enforcement information.

Tracking the Process of Issuing Permits

An abbreviated flow chart of the permitting process is shown in Figure 2. On the chart, the steps in permitting are shown as boxes with bold arrows; steps for the WPLCS database are shown as curved boxes. The flow of information between the WPLCS database and permit writers is shown by dashed arrows.

WPLCS keeps track of which facilities have submitted their applications and whether the applications are complete. It can also track whether permit fees have been paid. Permit mangers can find out whether someone in another region has written or is writing a permit for a similar type of facility. WPLCS can also show the limits and monitoring requirements in old and new permits for similar facilities, or for facilities located in the same drainage basin, and can name an Ecology contact for each one.

Once the permit manager begins writing the permit, WPLCS can provide data from past discharge monitoring reports and compare the results to existing and proposed effluent limits. A review of past data from the facility may suggest additional monitoring requirements, or identify extraneous ones. Monitoring data can also be used to predict possible problems with certain processes or waste treatment at the facility. These issues can then be addressed in the permit.

Information from WPLCS can be retrieved to assist in writing the published fact sheet on the proposed permit. WPLCS tracks when, where, and by whom public notice of the proposed permit was provided.

Analyzing Patterns and Trends

Since WPLCS stores data on many permits in a consistent manner, the system allows data to be combined for meaningful summary reports. By combining monitoring data, WPLCS can calculate mass loadings of pollutants by facility, industry, Water Resource Inventory Area, or drainage basin, or even for the entire state. Year-to-year effluent comparisons can be undertaken to verify discharge reductions. "Problem" chemicals or processes can be tracked over time and compared across the state. The possibilities are limited only by the time and resources available to research and enter historical or missing data into the database, ask questions and retrieve data.

Ecology is currently implementing an integrated basin-planning approach to environmental quality. One of the results of this approach is that a given basin will be targeted for permitting, inspections, and ambient monitoring on a rotating basis. In addition, staff will conduct more intensive analysis of water quality in a given basin, in order to determine overall effects from multiple sources. Analyses may include listing known and permitted point sources, calculating loadings, assessing assimilative capacity, and relating discharge monitoring information to ambient monitoring data. For more information on the basin-planning approach to water quality management, contact Ron McBride at (206) 407-6469.

Making Policy Decisions

WPLCS can be used as a tool for making decisions regarding permit requirements, permit limits or the need for enforcement actions on a case-by-case basis because it will maintain a history of such information.

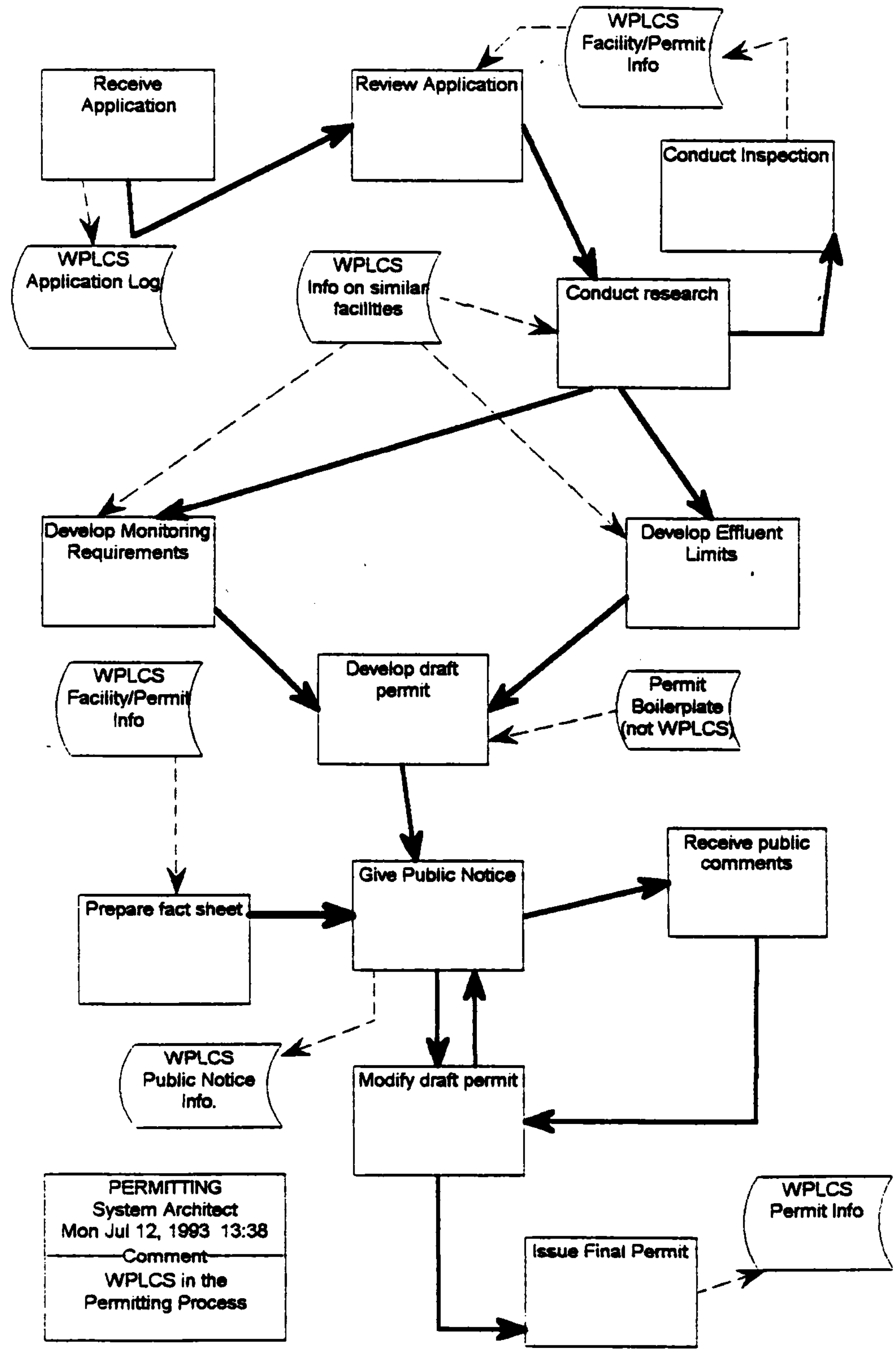

Figure 2. WPLCS in the permitting process

In addition, WPLCS can provide information that will enable regional or program-wide policy decisions to be made on issues such as:

- the optimal design of facility treatment systems;
- the feasibility of "ratcheting" down permit limits over time;
- the best monitoring program design for certain facility types or industrial processes; and
- the redesign of water quality permits to more clearly specify limits or monitoring requirements.

EPA's philosophy for the NPDES program has changed in the past five years from developing permits and permit limits based on available control and treatment technology to developing permits based on the facility's past or potential impact on a drainage basin. This change necessitates moving away from dealing with facilities or permits on an individual approach to one that integrates information for a basin. Ecology could not implement such an approach without an information management system such as WPLCS.

Making Management Decisions

WPLCS can be used by regional and Water Quality Program managers for workload planning and budgeting. For example, WPLCS can generate a list and count of the number of facilities in each region with permits that are expired, extended, or about to expire. To help set priorities among facilities, WPLCS data could be retrieved to describe the types of facilities, the basins in which they are located, their relative contribution of pollutants, or the number of violations at one facility as compared with others. Priorities for enforcement actions could be set by looking at enforcement histories, patterns of violations, or particularly sensitive drainage basins.

Monthly management summary reports, previously generated by hand, have been generated from WPLCS since July 1993. The reports list the number of existing permits, new permits issued, inspections of various types, enforcement actions of various types and other activities that have taken place monthly in each region. Reports can be generated by quarter and fiscal years, and graphs can track changes over time. Table 2 shows an example of a monthly summary report.

OBTAINING WPLCS DATA

To obtain more information on WPLCS or obtain WPLCS data, contact Tim Hilliard at (206) 407-6429 (or Internet mail THIL461@ECY.WA.GOV). He will be able to discuss your needs in detail and get you the data. The simplest way to obtain data is to ask for a run of an existing report (e.g., "I'd like a standard facility list for the Southwest Region, sorted by county"). A special request costs Ecology time and effort spent in writing special computer programs, and it will take more time to get your data. Some costs may apply and some data may be available in electronic form only. A "Request for Public Record" form must be filled out before receiving data.

Table 2. Sample WPLCS summary report

For Whole State
From: 1-Nov-94 Through: 30-Nov-94

No. of APPLICATIONS	Total Received	Renewal Accepted	New Accepted
STATE INDUSTRIAL TO LAND	0	2	0
STATE INDUSTRIAL TO POTW	5	0	0
STATE MUNICIPAL	2	0	0
NPDES Municipal Treatment	5	1	0
NPDES Concentrated Animal	0	0	0
NPDES Industrial	3	1	0
NPDES New Sources & New Discharges	0	0	0
NPDES No Process Wastewater	0	0	0
NPDES Storm Water	0	0	0
GEN. HATCHERY	0	0	0
GEN. BOAT YARD	0	0	0
GEN. SAND & GRAVEL	8	0	69
GEN. DAIRY	0	0	0
GEN. FRUIT	16	0	12
GEN. STORM WATER	0	0	0
Total No. of Applications	39	4	81

No. of PERMITS ISSUED	New	Renewal	Temporary	Modified
MAJOR - NPDES	0	0		0
MINOR - NPDES	1	6		3
STATE TO LAND	1	1	0	1
STATE TO POTW	0	0	0	0
GENERAL Total 204				

TOTAL PERMITS *	Current	Extended	Expired	Temporary	Unknown	Total
MAJOR - NPDES	76	9	0	0	0	85
MINOR - NPDES	214	150	73	2	0	439
STATE TO LAND	66	35	19	54	0	174
STATE TO POTW	87	10	4	58	0	159
Total No. of Permits	443	204	96	114	0	857

GENERAL PERMITS	Hatchery	Boat Yard	Sand/Gravel	Dairy	Fruit Packer	Storm Water	Total
Total	92	115	350	0	241	1801	2599

No. of INSPECTIONS	Recon.	CLASS I	CLASS II	Maintenance	Outreach
MAJOR - NPDES	0	2	0	0	0
MINOR - NPDES	4	10	1	0	8
STATE TO LAND	1	5	0	0	0
STATE TO POTW	0	0	0		
GENERAL PERMIT	1	3	0		0
ACTIVE UNPERMITTED FACILITIES	2	0	0		
Total No. of Inspections	8	20	1	0	8

No. of OTHER INSPECTIONS	
PRETREATMENT AUDIT	0
UNDERGROUND INJECTION CONTROL	0
PRETREATMENT COMPLIANCE	0

No. of ENFORCEMENT ACTIONS	Warning	NOV	Order	Penalty
MAJOR - NPDES	0	0	1	0
MINOR - NPDES	0	1	2	0
STATE TO LAND	1	0	0	0
STATE TO POTW	0	0	0	0
GENERAL PERMIT	0	0	1	0
ACTIVE UNPERMITTED FACILITIES	0	0	0	1
Total No. of Enforcement Actions	1	1	4	1

* TOTAL PERMITS 3456

* Note: Totals are current at print date.

STRANGE AND MYSTERIOUS WONDERS: HOW NEW COMPUTER TECHNOLOGY CAN HELP US MANAGE PUGET SOUND

Roberta P. Feins[1]

INTRODUCTION

This article is a meditation into our ability to manage environmental data in a way that supports our goals and methods of environmental management. As such, it is not a research paper, but a point of view, developed from my own experience of 16 years with computers and backed up by anecdotal evidence. I would welcome comments or discussion.

My thesis is that our approaches to environmental data have paralleled and even mimicked our approaches to environmental management over the years—from a centralized national technological approach in the 1970s, to the proliferation of environmental programs and processes in the 1980s. With the "maturation" (if one can call it that) of our approach—for example, recognizing the importance of local involvement in environmental decisions—comes a new set of needs for information. It is only recently that we have had the information management tools to support this approach.

THE "OLD DAYS": 1960s AND EARLY 1970s

Since the early moments of the environmental movement in the 1960s, computers have been used to manage environmental data with the goal of improving our ability to make good management decisions about resources. The EPA Storet system (Storage and Retrieval System), one of the larger water quality databases, was started in the early 1970s, about the same time that EPA was formed. The National Oceanographic and Atmospheric Administration's National Oceanographic Data Center (NODC) and the U.S. Geological Survey Water Data Storage System (WatStor) also originated at this time.

In the early days, the problem of environmental regulation was viewed as largely a technical problem, and one that could be solved by expertise. EPA took on this expert role, defining the best treatment technologies for waste, determining safe levels of certain chemicals in drinking water and air, and deciding the best uses of various bodies of water. A national permit program was developed; it was called the National Pollutant Discharge Elimination System, because it was believed we could eliminate pollution in 20 years.

During this same period, large mainframe computers were the only tools for managing the information collected by these programs. These machines were good at storing and processing large volumes of data, but they required a lot of intensive programming and technical expertise to manage data. The early databases—Storet, NODC, WatStor and EPA's Permit Compliance System (designed to manage NPDES data)—were developed as enormous sequential files, in an 80-column format that could be input on punch cards. This creation of massive databases on large computers tended to parallel our centralized approaches to environmental management.

Both the management systems and the computer systems lacked flexibility. Intermediaries and experts were required to obtain and interpret the data. As the Storet and Permit Compliance System (PCS) database began to be populated with data, the types of information that could be retrieved were very limited. Users could get massive printouts of the data, with a choice of perhaps two different formats. Requested reports were created by programmers and mailed to requesters' offices—with a turn-around time of several days.

EPA staff and consultant programmers have spent a lot of time (and money) over the years in developing ways to make Storet data more accessible. Some simple menus were developed, allowing users to pick a variety of report formats. You could also get certain kinds of graphs or maps. However, because

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of the hardware and software being used, developing these tools for users was very time- and labor-intensive. Programmers were always working to catch up with user demand.

The net result of this was that people began to view these systems for managing information as flowing in one way only—to the centralized database. EPA let data entry contracts to add data to the system. States and researchers would collect data for regulation or for a research project and would send data to NODC or PCS after they were finished using it. There were a limited number of computer terminals available to government staff, so only a few used the databases. Researchers at universities had access to university mainframes and worked with data there in models and statistical packages (e.g., BMDP or SPSS).

Since people didn't use the data very much themselves, there was often little assurance of the quality of the data that ended up in these centralized databases. I heard estimates in the mid-1980s that 25 percent of the data in Storet was either missing or in error. For example, spatial coordinates for sampling stations were often omitted; even today, if you try to generate a map of sampling stations from Storet, a great many of them are on the equator (0 latitude, 0 longitude).

These problems with centralization and the need for technical expertise were recognized early on, and there was progress over the years in dealing with them. The legal language of the Clean Water Act allowed EPA to delegate permitting authority to the states, so that the permit program would have some flexibility to meet local conditions.

As program authority was delegated to the states, states began developing their own data systems to allow them direct access to data. Thus duplicate systems with similar functions were developed on the state and federal level. It is unlikely that the data in both systems were the same, given that in some cases data were entered twice, and in other cases, data required reformatting to be transferred between systems. Initially, the state systems were also developed on mainframe or mini-computers and presented the same problems with access and useability. However, the advent of personal computers in the 1980s changed the picture considerably.

THE 1980s

The 1980s could be characterized as a time of distribution and proliferation in both environmental and information management. The federal government continued to distribute and delegate authority for environmental decision making to the states (although it has distributed less and less money to fund these programs). Laws such as the Federal and State Environmental Policy Acts (SEPA) required a wide variety of types of information to be used for assessing the environmental impact of proposed projects. These laws also laid out the first concepts of the importance of the public involvement process in making the correct environmental decisions. Decisions were no longer viewed in purely technical terms; the method of arriving at them was also important.

The term proliferation is appropriate because this period saw a enormous increase in the number of environmental programs, as we tried to deal with our recognition of the complexity of the problems. Laws such as the Resource Conservation and Recovery Act (Superfund), the Toxic Substances Control Act, and the amended Clean Water and Clean Air Acts set up new programs on non-point source pollution, stormwater, resource recovery and recycling, hazardous waste handling, and disposal. In general, government's response has been to set up new offices and new databases to implement each of these programs.

The advent of personal computers in the 1980s meant that these trends in environmental management were echoed by trends in information management. The fact that large centralized databases were so inaccessible led to the proliferation of small data systems on single-user computers. Each research project or separate program had its own project database, often in a spreadsheet. Such systems were immediately accessible and easy to use for a single user, but not easily available to anyone else.

The availability of user-friendly software made unnecessary the expert intermediary between users and their data. Word-processing packages, spreadsheets, database software, graphics and desktop publishing all offered a widely expanded array of options for analysis and presentation of data. This served environmen-

tal management needs, since data could be presented, graphed and mapped in forms that facilitated communication with the public or other decision-makers.

Desktop availability of personal computers allowed people to access data directly in remote systems, such as Storet or WatStor. The expanded analysis tools available in these centralized systems and databases, such as the Ocean Data Evaluation System (ODES), also provided users with options.

At the same time the proliferation of these systems meant that data on the same topic might be stored in five or six different spreadsheets even within a single agency unit. "Sneaker net"—carrying data on a floppy disk across the office—was used to exchange information. Data from these different systems would have to be extensively reformatted to be combined. Such time-consuming reformatting was done as infrequently as possible. This made it hard to get an integrated view of environmental conditions. Efforts such as Ecology's Environment 2010 initiative spent a considerable amount of time and effort integrating information to achieve a limited picture of current environmental conditions. The public received highly processed information in a format judged suitable for them; it was difficult to get answers to a slightly different question.

The small single-user systems often lacked adequate control over data quality. Data were not protected against unintentional change. Information (e.g., station or industrial plant names) would be updated in one system and not in another. Data were often poorly documented because although the person who set up the spreadsheet understood the data very well, too often that person left, or sent the data to someone else who was unable to understand and interpret its context.

The problems among agencies were similar to those within agencies: Different software was used on a variety of databases, which were not comparable and could not be shared. In my experience it has often been faster to reenter information into a project database than to try to reformat and document data received from a different database. I shudder to think of the amount of money wasted in such redundant data entry. Even now, EPA and Ecology each enter monitoring data from NPDES-permitted facilities into their respective databases, PCS and the Wastewater Quality Permit Life Cycle system (WPLCS).

People recognized the dangers of the proliferation of small un-integrated databases, but these single-user systems answered a deep need for direct access and analysis of data. The larger centralized databases developed in the 1970s were unable to change to meet this need. Textbooks in computer system development estimate that systems need to be redesigned and replaced every five to ten years as technology and needs change. However, funding for modifications and redevelopment has always been scarce at the federal level. In the 1980s, EPA attempted to expand Storet to handle sediment and biological data, but funding cuts paralyzed this effort.

In Puget Sound there was a move in the late 1980s toward better standardization of data. The Puget Sound Protocols specified standard protocols for chemical analysis of sediment, water and tissue. Standardized forms for documenting and exchanging data were developed for both the Puget Sound Ambient Monitoring Program and the Puget Sound Dredge Disposal Analysis. Both of these programs focused on the distribution of data among agencies with authority for decision-making and on an eventual regathering of data in a centralized archive.

THE PRESENT AND FUTURE

What is driving change in environmental management at present? There are major changes under way as a result of the recent elections. But still, we are clearly moving toward a more local and more multi-player approach to decision-making. Efforts such as the Chelan Agreement and watershed planning focus on bringing together all interested groups in the on-going process of forging a vision and making it come true.

As the information required for decision making gets more diverse, participation is becoming much more sophisticated. Increasingly, the parties in these decision-making processes have the sophistication to ask complex questions and the technical abilities to work directly with information. They will no longer be satisfied with a single display map but will want information on an ongoing basis.

As state government grows larger and more complex, there is a need for more careful tracking of program activities. The retirement of staff that were around when the programs developed in the 1970s and constant staff shuffling due to budget cuts means a great loss of information in "mental databases." This makes it even more imperative that agency information be codified in computer databases.

Recent advances in computer technology allow us to envision a group of computer systems that would be integrated yet tailored to individual or agency needs. Such a system would mimic our more decentralized (or many-player) approach to environmental involvement and decision making.

The development of networks enables many users to use the same data while allowing database managers to maintain control over the content of their databases. PCs and networks allow users to create, format, enter, perform quality assurance and work with data locally, while making the information accessible to other users in nearby or remote locations. While database managers can control content and quality, they do not limit the uses to which data are put. Users have access to the whole range of tools available on personal computers for data analysis and presentation.

The Wastewater Quality Permit Life Cycle System (WPLCS) is the first Ecology database to use this technology. Each Ecology regional office (Northwest, Southwest, Central, Eastern and the Industrial Section in Olympia) has installed a version of the WPLCS database that contains data for facilities and permits in the region. The regional databases are accessible to local staff via their computer Local Area Network and accessible from other offices (and other agencies such as EPA) via the Ecology Wide-Area Network. This arrangement allows data to be managed and updated locally, but it is accessible to users across the state. Data can be readily retrieved in the form of listings, graphs, spreadsheets or text for word processors.

Such systems can obviate the need for users to create a new spreadsheet or database for each project or each function an office performs. Using good design practices, a standardized model of environmental data can be developed, allowing it to be used in different ways to meet multiple users' needs. For example, the WPLCS system stores a list of all NPDES-permitted industrial facilities in a region; these data can be used to count the number of permits, to estimate workloads for permit renewals, and to calculate potential revenues under various permit fee schedules. Effort is spent only once on entering the data and keeping it up to date. The potential uses are unlimited.

With the availability of wide-area networks, such an approach can also work across offices and across agencies. Currently, a user at EPA can log on to Ecology's network and get a list of facilities, or a list of monitoring data out of WPLCS. Over time, it is conceivable that such an approach could eliminate the need for EPA's parallel and duplicative PCS system. Tools are becoming available that would make such access across a network transparent to a user. An EPA staffer, not a computer expert, could sit down at a terminal anywhere in the United States and get a listing of facilities in Washington state. The EPA network would maintain a list of addresses at which data of certain kinds could be obtained, and the network software would contact the correct Washington state computer, transmit the appropriate commands, and return an up-to-date list of facilities.

Another example is the Puget Sound Geographic Information System (GIS). In the early 1990s a major effort was undertaken to move information from the Puget Sound Environmental Atlas into a computerized system that would allow more diverse data uses. Currently, the Puget Sound GIS is stored and managed centrally by the Aquatic Lands Division of the Department of Natural Resources. Data is updated every few years by working with experts in each area.

For the future, imagine a system where each agency responsible for a type of geographic data maintains that portion of the GIS. For example, the Department of Health would use data on shellfish beds on a day-to-day basis as part of its monitoring and testing programs for contamination. A GIS user, (a high school student, businessman, agency representative, consultant or researcher) could sit down at a terminal and dial the Puget Sound GIS. Menus would allow the user to combine shellfish bed locations in the user's watershed of interest with data from a local tribe on fish habitat in the watershed to create an up-to-date map. The data would be retrieved from several different computers; the map could be displayed on the user's PC screen, downloaded to a local printer or saved for further analysis.

What is needed for us to move into this promising future? Some federal systems are moving in this direction. While EPA's new Storet database will be a centralized system, the U.S. Geological Survey is putting its National Water Information System on regional mini-computers, connected by a nationwide network.

Obviously the funds to develop these networks and gateways to link offices and organizations is a critical ingredient. Money currently being spent on maintaining inefficient systems or on reconciling disparate or partially redundant databases could be used for redevelopment. Careful work in information planning and design is needed to ensure that new data systems can be integrated. Keeping the data under local control and encouraging people to use them on a daily basis are the conditions needed to promote data quality.

THURSTON REGIONAL WETLAND AND STREAM CORRIDOR INVENTORY

Steven W. Morrison[1]

INTRODUCTION

In Washington state and particularly within the Puget Sound region, local governments find themselves facing the challenge of protecting wetlands without adequate resources. Unfortunately the federal government and state agencies have not yet developed a standardized wetland inventory methodology. Although often mentioned as the wave of the future, the current resolution of remote sensing from SPOT or ERTS satellites was found to be too inaccurate for local needs. Aerial photographic interpretation (similar to the National Wetland Inventory) is a means of mapping a large area; however, it lacks adequate detail for many uses. Field-intensive inventories generate adequate detail, but are generally limited to smaller areas because of their higher cost. The most cost-effective current option has been to combine the advantages of aerial photographic interpretation with a limited field reconnaissance through the use of a Geographic Information System (GIS).

THE THURSTON REGION

Thurston County, Washington, is a rapidly urbanizing county at the southern terminus of Puget Sound, 60 miles south of Seattle. Olympia, the state capitol, lies at the heart of this urbanizing area, which also includes the neighboring cities of Lacey and Tumwater. In the southern part of the county lie four small towns. This 717-square-mile county includes a diverse geographic mixture of low foothills, peninsulas, prairies and river valleys as a result of the Pleistocene glaciation. Wetlands are most common in northern Thurston County and can be found along the 106 miles of Puget Sound shoreline, adjacent to the county's 107 lakes, or in association with the three major river systems. The existing National Wetland Inventory and Soil Conservation Service maps of hydric soils indicate that approximately 8.0 percent of Thurston County is covered by wetlands, with another 1.4 percent being covered by lakes or ponds.

Thurston Regional Planning Council (TRPC) is a 15-member intergovernmental board made up of local government jurisdictions within Thurston County including Olympia, the state capitol. The council was established in 1967 under a state law authorizing the creation of regional planning councils. TRPC undertakes land use, environmental and transportation research and planning programs of interest to the member jurisdictions. The council is governed by representatives from the member jurisdictions, and each member funds the council's operations based on a per capita formula.

PHASE I: PILOT PROJECT

In 1989 the Thurston Regional Planning Council initiated a wetland pilot project to address its regional needs. The goal was to produce reasonably accurate wetland and stream corridor maps of both urban and rural areas at an affordable price. TRPC began the wetland mapping program as a first step, while recognizing that a wetland ranking system requiring field information could be added at a later date. The pilot project mapped the wetlands in 21 square miles of northern Thurston County and was funded by two Coastal Zone Management grants totaling $50,000 administered by the Washington Department of Ecology (Ecology).

The pilot project was divided into three north-to-south flight lines, centered along section boundaries. The technique explored by the pilot project included the use of aerial photography interpretation and field verification. The mapping data from these tasks were then digitized into the Thurston Geographic Information Facility GIS computer to compare the accuracy of different mapping sources and to create wetland maps. The pilot project budget was adequate, even with several additions, as the actual time

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needed for tasks by the wetland consultant closely paralleled the project estimates. Recommendations from the pilot project provided the basis for the second phase of this county-wide wetland inventory.

PHASE II: NORTHERN COUNTY INVENTORY

The primary goal of Phase II was to refine the inventory techniques developed in the pilot project and apply these to a larger geographic area. The northern county inventory mapped wetlands and stream corridors within a 306-square-mile area of northern Thurston County. This included the cities of Olympia, Lacey and Tumwater; the Urban Growth Management boundary; and other portions of unincorporated Thurston County. The study area included a wide variety of land uses as well as soil and habitat types. Generalized land uses included agricultural, suburban, urban, forested, private and public lands. The pilot project study area was also remapped, but the Fort Lewis Military Reservation and land designated as Long-Term Forestry zoning district were excluded from the inventory, since local governments have limited jurisdiction in these areas.

Eleven "special study areas" were selected for field reconnaissance. This represented 52 square miles or about 17 percent of the study area. These areas were selected by TRPC, with input from its member jurisdictions, to provide a representative sample of various wetland types. Special study areas usually included a small drainage basin or followed a stream corridor. A secondary purpose of the field reconnaissance was to collect enough field data to evaluate Ecology's *Wetland Rating System for Western Washington* (1991).

The inventory process began by flying a completely new set of false color infrared aerial photographs flown during the spring and before leaf-out. The project's most significant problem occurred when the original aerial photo consultant could not meet this deadline, and the entire project was delayed a year until the spring of 1992. A wetland consultant was then hired to provide the aerial photo interpretation and to field-check the wetland boundaries and wetland ratings within the special study areas. The data from the photo interpretation and the field reconnaissance was again digitized and loaded onto the GIS computer, which also contained the county's tax parcel or assessor's maps.

The most important product of the inventory was the production of the wetland and stream corridor maps by square mile, often referred to as sections. These maps are in color at a scale of 1 inch = 1,000 feet, which is large enough to also show individual property lines. They indicate whether wetland boundary is "certain" or not, a description of the type of wetland habitat using the National Wetland Inventory (Cowardin) system, and the Ecology rating of the wetlands within a special study area. These maps have been of great interest to property owners, developers, assessors, real estate agents, engineers, conservationists and regulators. In addition to the individual maps, other available products include a composite a map of the Northern county inventory, tabular and graphic databases, and custom maps upon request.

For a more complete description of the techniques associated with this inventory refer to *Thurston Regional Wetland & Stream Corridor Inventory: Phase II—Northern Thurston County* (1993), which is available from Thurston Regional Planning Council.

EVALUATION OF WETLAND INVENTORY TECHNIQUES

In most cases the differences between the pilot project and the northern county inventory were found to be small even though the increase in area was almost 15 times. But even with a successful project the learning curve for some of the techniques was very steep. Following are some of the more significant findings.

Wetland Ratings

Most jurisdictions in Washington state that are planning under the State Growth Management Act have adopted Ecology's four-tier rating system. However, it was not well understood how such a system would fit a community with relatively abundant number and size of wetlands, such as the Thurston Region. TRPC worked with Ecology to create a wetland rating system database for the special study areas. Of the

380 wetlands located within the special Study areas, 26 percent were found to be Class I (highest quality) wetlands. However, if evaluated on the basis of area, the amount of Class I wetland increases to 77 percent. The data base indicated that the predominant cause (62 percent) of a Class I rating was the presence of "organic soils," when in fact the intent had been to identify "bogs and fens." TRPC's evaluation of this wetland rating system contributed to an update of this system in 1993.

As the first independent evaluation of Ecology's rating system, it turned up some interesting results. However, the rating of wetlands took a significant amount of staff time and in some ways may have inadvertently shifted the emphasis of the inventory away from its primary goal to provide accurate wetland maps. Since wetland ratings have been further refined by the state and within local critical areas ordinances, there should be no need to duplicate this effort.

EPA's Water Body System

The use of the EPA Water Body System was one of the least successful techniques employed in this project. The "Water Body System User's Guideline Codes" allow those with little background in water quality to adequately categorize sources of water quality problems. This was believed to be an important component, since the inventory was funded by a "Clean Water Grant." These codes were noted during both the aerial photograph interpretation and during field reconnaissance tasks.

Problems occurred in both the photo interpretation and field reconnaissance phase. It was difficult to observe point source water quality problems from the aerial photos. Field-locating water quality problems was not the first priority for the wetland consultant. It was also apparent that the field teams were not as experienced as local government staff at spotting potential water quality violations, when a tractor cleaning out a drainage ditch was not noted as a problem. Additional protocol needs to be developed if EPA's Water Body System is to be an effective tool.

Aerial Photo Quality

The aerial photographs for the pilot project were processed as a negative and then as a print. Although this was a less expensive process than producing prints from a positive slide, it is not a technique which Kodak recommends. For the northern county inventory the film was processed as a positive slide, and then a direct Cibachrome print was made. Glossy prints were chosen over a matte finish, since glossy prints generally hold up better under field conditions.

The aerial photographs produced for Phase II were of higher quality and clarity than those used for the Pilot Project. The increased clarity made a significant difference in colors and hence produced more distinct photographic signatures. This enabled the photo interpretation team to more readily distinguish different habitats, particularly unique wetland plant associations such as bogs and estuarine emergent wetlands.

Multiple Scales of Aerial Photography

The pilot project used an aerial photo scale of 1 inch = 1,000 feet (1:12,000). At this scale a square mile fits within the center 6-inch square, which contains the area of least distortion due the curvature of the camera lens. However, this scale also limited the interpretation of wetlands to about 0.4 of an acre. The local jurisdictions wanted to regulate wetlands larger than 0.25 acre, so a second set of 1 inch = 500 feet photos was flown for the Olympia-Lacey-Tumwater urban area.

There were a number of increased costs, which were a direct result of using the 1 inch = 500 feet photos. First, they increased data management costs because there were four photographs for every one at the 1,000 foot scale. It also created problems in edge matching section maps of different scales, which occurred along the boundary of the urban area photo coverage. Distortion and variances in registration required editing to match polygons. Though some small wetlands were identified that probably would not have been identified using the 1,000 foot scale photographs, the number of these wetlands was very small. The rating portion of the project also found that most small wetlands are of low quality (rating of III or IV

in the Ecology system). Therefore, the aerial photo scale of 1 inch = 1,000 feet provides the best all-around product.

Edge Matching and Map Editing

The initial differences between the pilot project, which had three totally separate flight lines, and this project were not fully appreciated. Before attempting such a project one should first be acquainted with the art of "quilting" to fully comprehend the complexities of matching 306 individual wetland sections. As a result, edge matching along the north to south flight lines proved to be too inefficient. Future mapping efforts should test out two modified techniques, one for the scripting process and the second for the plotting-editing process.

Instead of using an individual sheet of Mylar for each section, multiple sections should be scripted together. This will not be as easy to store but should provide greater coordinate control and result in a more accurate rubber sheeting process. Larger Mylars would require more initial edge matching by the wetland biologist but should reduce the number of subsequent edits. Suggested script sizes are 4 x 4 sections or quarter townships (3 x 3 sections).

The edge matching for this project was essentially completed after all individual sections had been digitized and edited once. The final comprehensive edge matching process required about 65 person-hours for the wetland consultant and considerable time for TRPC to make these edits. Instead of editing individual maps, it would be more efficient to plot preliminary wetland maps together to complete the initial edit. If these wetland sections were plotted by townships (6 x 6 sections), then two edits could be completed on the same map in one step.

Private Property Access

Accessing private property for a government-sponsored project is never easy. In the pilot project TRPC used a formal letter to contact wetland property owners about the field work. The letter explained the project and asked landowners to contact TRPC if they did not want the wetland consultants to visit their property. This letter generated a response rate of only 5 percent. Of these respondents about 35 percent denied access to their property. While the percent denying access in both projects appears constant, the rate of response for the northern county inventory was 15 percent higher than that for the pilot project. This was probably due to four factors: The pamphlet contained more information, i.e. included the field verification dates and provided the property owner a range of responses including feedback comments, and most packets included a return envelope.

Property Owner Contact

In the field, interactions between landowners and wetland scientists were polite, positive, and concise. Occasionally, situations arose where landowners showed a great deal of interest in the inventory process, and had long conversations with field scientists. Some retirees seemed to be especially talkative, often relating the local history of the area, their personal life stories, gossip about their neighbors, and discussing the great floods of previous years. Discussions with these folks often were informative and helped the scientists understand the hydrologic systems even though the field work was being done during the driest time of the year. Some landowners, retirees included, gave tours of the wet spots on their property and were quite agile at beating the bush through dense shrub or forested areas. Compared to the pilot project, however, less overall time was spent talking with landowners than during the field work for this large inventory.

Public Education Techniques

The overall impact of public education techniques aside from the property access pamphlet are difficult to gauge. Two Stream Team workshops were less successful than hoped because they were scheduled too early for most of the special study area mailings. Personal presentations in the local area were generally well received even though this was a rather hot topic. School presentations were always fun and an excellent warm-up for presentations to elected officials. The wetland display panels were invaluable at

presentations and led to a greater confidence about the project. The brightest spot was the front-page newspaper article and color picture running right before our second Stream Team Workshop.

Public education is always identified as a key way to change attitudes. However, effective public relations takes time, money and a lot of work. Unfortunately, much of the public education budget was shifted to address the private property access. While public relations about the maps has been generally favorable, the limited budget did not allow for a big wrap-up presentation to the community. Therefore, the ability to field-check questionable wetland boundaries should be carefully weighed against the project cost to obtain that access.

Photo Interpretation Problem Areas

Wetland maps derived from photograph interpretation were evaluated for accuracy and precision by field reconnaissance of the special study areas. In general, accuracy varied among wetland classes, with forested wetlands being the most difficult areas to map. They were often overestimated in size and occasionally were found to be uplands. Certain tree species and certain plant associations were helpful in identifying questionable forested signatures as forested wetlands. The photographic signatures of soft rush was often a co-dominant species with reed canary grass in wet pastures, and so this was an aid to correct identification.

No differences were found in the precision of field-verified boundaries as the season progressed. Aquatic bed vegetation was generally not visible in the early spring aerial photographs and so was classified as open water. Some wetlands that appeared as open water in early spring were dominated by emergent species later in the growing season. Estuarine wetlands were often masked by high tides, and their occurrence may have been overemphasized along some stretches of shoreline. The increased quality of the aerial photographs most likely allowed for easier wetland interpretation. However, restricting field reconnaissance to only the preselected special study areas probably reduced the accuracy of other areas with questionable wetland signature or boundaries.

False Positives

The TRPC staff has been responsible for the updating of the wetland inventory over the past 18 months. During that time many people have commented on how accurate the boundaries are. However, there have also been a number of cases where the inventory has reported a false positive, or mapped a wetland that does not exist. This has been the most predominant mapping error found in the inventory. False positives have occurred mostly in forested wetlands, but also some Scot's broom patches were identified as scrub-shrub wetlands. These mapping errors have placed the credibility of the entire wetland inventory in doubt for at least one Thurston County planning commissioner, who had the only wetland in an entire section. The Port of Olympia also has questions about the inventory in its ownership around the Olympia Airport. On another site near the airport, we were told "you could check this one out at 45 miles per hour" as it was a recently-cut Scot's broom patch.

Thankfully, none of these errors have occurred within a special study area. It is apparent that the screening protocol for checking soil types and the NWI maps after a section was delineated was not entirely effective. This protocol may have placed too much reliance on the skill of the wetland photo interpreter. Wetlands that were identified as an outwash or as Class I excessively drained soil should have raised a red flag. A check on these situations would likely have addressed the errors on both the planning commissioner's and the Port's properties. Therefore, new wetland section mapping should be screened by a GIS computer to highlight areas of nonhydric soils that should be field verified.

Project Management and Budget

The single most limiting factor for the transfer of this project protocol is its cost. The wetland inventory would not have been possible without grant funding. The Washington Department of Ecology funded both phases, with a Coastal Zone Management grant for the pilot project and a $287,000 Centennial Clean Water grant for the northern county inventory. Significant local financial assistance was also

provided by the stormwater management divisions of the Public Works departments from the cities of Olympia, Lacey, and Tumwater. Thurston County also participated through both its Road Operations and Stormwater divisions. As a result, the cost to TRPC has been greatly reduced.

The average per-square-mile cost for the northern county inventory was approximately $950 (in 1993 dollars). This compared with a $2,300 per square mile cost for the wetland pilot project. The pilot project costs were significantly higher because of the increased management and start-up costs for what was an experimental project. The pilot project did not include wetland ratings, but it did provide 100 percent field reconnaissance versus only 17 percent for the northern county inventory.

The most significant budget change occurred in the data entry and mapping task, which increased by 63 percent. Earlier estimates of the time required to digitize each Mylar were found to be over-optimistic, and the impact of using the 1" = 500' mapping within the urban areas was not fully appreciated. Digitizing of the preliminary wetland boundaries was found to be very physically draining, and as a result the production rate varied greatly between the TRPC graphics staff. Of the four staff members who worked on these maps, none are current employees. In addition, the editing process used a much larger portion of the budget than expected. Editing of the maps was a major activity for both the consultant and the graphics staff.

The other major budget shift occurred in the public education task. It was earlier believed that an article in the *County Connection* newsletter could serve as an adequate public notice and information on property access. Discussions with our legal advisory indicated this would not be suitable and that direct contact would be necessary. (The response to this 40,000-piece mailing would later prove this point, with less than a half dozen contacts.) However, notifying each wetland property owner would cost significantly more than originally budgeted. The agreed-upon solution was to create a property owner pamphlet, which could be mailed, left on front doors, or handed out directly. Of these options, direct mail appeared to be the least expensive, and a wetland intern was hired to coordinate this effort. Having the wetland intern be totally responsible for this one task ended up being one of the best management decisions of the project. The cumulative results of losing one year due to the late aerial photos, a six-month extension in the project, and overages in the data entry and public education tasks resulted in fewer types of maps and less analysis by various features than desired. Because the sequencing of tasks was a key both for the wetland consultant and TRPC graphics staff, shifts in timing often caused a cascade effect. These unforeseen delays increased the project budget, and the 5 percent grant contingency proved to be essential for project completion. Monthly project reports were provided to Ecology and proved to be an excellent early warning system. This resulted in fewer surprises and better cost control than quarterly reporting would have allowed. Only at the end of the project did the staff truly realize that the northern county inventory was much more of an "experimental project" than the pilot project had been.

Over the last five years, TRPC has expended $340,000 of state and local funds to develop the mapping protocol and complete the northern county inventory. Grants were available on the basis of a pilot or demonstration project. However, once these were completed, TRPC has failed twice to secure a Centennial Clean Water Grant to complete its mapping of the remaining 275 square miles of southern Thurston County. As a result, other funding sources are being employed, including a portion of a Flood Control Assistance Account Program within the Deschutes River watershed. Given the fact that the mapping is too expensive to be done with only local resources and given the reduction of grant funding sources, it will be extremely difficult to complete the county-wide inventory in a systematic fashion.

CONCLUSION

The major failure of this project has arisen from the fact that the TRPC staff knows of no other jurisdictions which have or will be attempting to map wetlands using these techniques. This leads one to wonder if it is "bad science" or "it just costs too much." The community consensus on the northern county inventory is that it is the best information available, even with its detractors. Since there always seem to be technical issues with an experimental project, these do not invalidate its usefulness to a wide range of local jurisdictions and agencies within the Thurston Region.

We are on the edge of a brave new world of remote sensing. By the year 2005 the available technology may provide an accuracy of a square meter versus 0.1 acre and a cost of only $100 per section instead of $1,000. Therefore, this wetland inventory may be one of the last of an era of human photo interpretation. However, without it, how many wetlands would have been lost in Thurston County while we waited for the technology to catch up? If prevention is the key to water quality pollution, then the cost of this program will have been worthwhile in meeting our local needs. For other jurisdictions, waiting for more reliable remote sensing data may be a wise choice, due not only to its cost, but also to the nationwide change in political agendas.

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WATERSHED-BASED ASSESSMENT OF WETLANDS USING A GIS

Steve Gray and Joel Freudenthal[1]

INTRODUCTION

Wetlands are part of the region's hydrological and ecological structure. They act as sources, sinks or routes for water, materials (e.g., nutrients, pollutants), energy, and biologic activity. Not all wetlands have the ability to act as sources, sinks or routes. This exchange depends on climate, soils, geology, topography, landscape position, and influence of human modifications. Maintaining this structure promotes a region's health and sustains its ability to survive disturbance (Roth et al., 1993). Unfortunately, Clallam County, like many other localities, lacks local information as to where and why wetlands occur, how they function, and what specific protection efforts are needed to maintain or restore these functions.

The Clallam County Department of Community Development conducted a pilot project, as part of the Washington State Wetland Integration Strategy (SWIS) initiative, to improve local knowledge of wetland locations and functions in support of wetland protection efforts. The study was designed to take advantage of existing data, or data that could be easily compiled. A geographical information system (GIS) was used to take advantage of existing digital data sets and the GIS's ability to process spatial data, and for establishing a computerized wetlands data base. This paper summarizes the GIS procedure used for updating, characterizing, and assessing wetland functions. SWIS is supported by funding from the U.S. Environmental Protection Agency.

STUDY AREA

The project area covers 98,018 acres in eastern Clallam County, and encompasses portions of two regional watersheds—Dungeness River and Sequim Bay. The lower watershed reaches are characterized by a nearly level to gently rolling coastal area that ranges from one-half mile to 12 miles wide. Bordering the coastal area are the Olympic foothills and mountains. Because of the orographic effect of the Olympic Mountains, annual rainfall in the study region is the lowest in western Washington, averaging just 16 inches a year. Federal forest and park lands located within the mountainous upper portion of the watersheds were excluded from the project area because factors in the upper portion of the watershed that govern wetland development and functions such as precipitation, geology, terrain, and land management differ greatly from the factors in the lower watershed areas.

GEOGRAPHICAL INFORMATION SYSTEM

Table 1 lists the type and source of existing digital data sets contained within the county's GIS used for this study. Most of this information was compiled at a scale of 1:24,000 (1 in. = 2,000 feet) or smaller. The GIS application software used was PC/ARCINFO running on a Pentium personal computer.

Other data used in conjunction with the digital data included: 1988, DNR 1:12,000 Othophotos, 1990 aerial photos, well log data, regulatory wetland delineation and rating studies, and wetland boundary determinations—county service to confirm presence of wetland on property. Field knowledge of the county's habitat specialist and other local professionals contributed to updating data in Table 1. Recent watershed and groundwater studies were also reviewed to identify regional concerns as they related to water quantity, water quality, and fish and wildlife habitat, for guiding data collection and analysis efforts.

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Table 1. GIS data sets

Data Name	Source
National Wetlands Inventory (NWI)	USFWS/DOE(digital data)
NWI Updated Areas	PSRBT
Hydrography	DNR
Watershed Boundaries	PSRBT/County
Irrigation Ditches	PSRBT
Priority Habitats and Species	DFW
Resident & Anadromous Fish	DFW
Non-Game Heritage Data Base	DFW
Natural Heritage Data Base	DNR
Significant Wildlife Movement Corridors	County
Soils	DNR
Surficial Geology	USGS/PSRBT(digital data)
Land Use/Land Cover	PSRBT/County
Zoning	County
Parcelization	County
Ownership	DNR
Transportation	DNR/County

Sources: U.S. Fish & Wildlife Service (USFWS); state departments of Ecology (DOE), Natural Resources (DNR), Fish and Wildlife (DFW); and Puget Sound River Basin Team (PSRBT). The PSRBT conducts watershed characterization studies for local governments.

WETLAND INVENTORY UPDATE

The NWI and local NWI updates were combined, plotted, and registered to the DNR orthophotos. For editing assistance, hydric soils, streams, and irrigation ditch locations were also plotted on the overlays. The registered overlays provided the geographic base for updating wetland boundaries. Wetlands were delineated by system (e.g., estuarine, palustrine), sub-system, and class (e.g., forest, emergent, open water), through a combination of stereoscopic photo interpretation and previous field observations, based on the USFWS classification system (Cowardin et al., 1977). No additional field work was performed, except for verification of wetland locations and plant communities previously not field-confirmed.

Each inventoried wetland was assigned a unique number. Since many wetlands contain more than one Cowardin wetland type, a unique code was also assigned to each wetland polygon. This dual identification system allowed data to be assigned to either the wetland or wetland community, eliminating data redundancies. Data items collected as part of the inventory update were acreage (calculated by the GIS), Cowardin wetland type, dominant plant types (e.g., mature conifers) and habitat features (snags, islands), upland buffer condition (percent cover type), modifications (damning, filling, excavation, etc.), management (pasture, residential, etc.), regulatory rating (if any), source of verification, and field visit date.

HYDROLOGIC CHARACTERIZATION METHOD

Based on observed regional flow patterns, wetlands were assigned to one of the following seven hydrology types: 1) perched water table discharges to stream; 2) perched water table, storage on till for detention/retention, discharges to stream; 3) locally perched water table with no or small outlet (discharges to aquifer); 4) aquifer discharges to wetland, wetland discharges to aquifer; 5) aquifer discharges to wetland, initiates stream; 6) aquifer discharges to marine, tidally influenced; and 7) perched water table

discharges to aquifer. An aquifer was defined as groundwater that can be withdrawn in sufficient quantities for human use. Perched groundwater conditions result from the presence of a shallow impermeable layer such as till, and normally do not supply enough water for human consumption.

The procedure involved overlaying the updated wetland inventory, surficial geology, soil, and hydrography data layers. The surficial geology units were classified to determine whether the groundwaters in that unit could be considered aquifers or perched water tables. It was assumed that the characteristics of water-bearing strata were generally uniform within a surficial geologic unit. Classifications were cross-checked with well log data.

Soils overlying the surficial geologic units were used to further establish wetland hydrology based on classifying wetland soil types into hydrogeomorphic units from soil descriptions in the local soil survey. For example, Bellingham soils indicate an enclosed basin with no or very slow drainage from the basin, while Mukilteo Muck soils indicate groundwater discharge to streams, due to landscape position (basins and valleys), high organic content, and seasonal water ponding. Approximately 59 percent of the mapped wetland acreage was classified as hydric. Hydrology types for those wetlands not located on mapped hydric soils were inferred based on associated soil inclusions, landscape position, and surficial geology. Hydrologic connection of surface waters to wetlands also provided indicators of wetland hydrology. For example, many of the region's smaller streams contain wetlands underlain by Mukilteo Muck soils in their headwaters, further indicating that such wetlands initiate streams.

HABITAT CHARACTERIZATION METHOD

Characterization of fish and wildlife habitat provided by wetlands was generally based on existing wetland assessment methodologies such as the Oregon Freshwater Assessment Method (Roth et al., 1993) and Wetland Evaluation Technique (Adamus, 1987). These methodologies assess habitat functions based on documented species use, habitat indicators (e.g., size, diversity) and connection to other habitats. Species use of wetlands and adjacent uplands was acquired by overlaying state fish and wildlife databases. Habitat indicator data was collected during the wetland inventory update and wetland hydrology characterization, as previously described.

Wildlife movement corridors were characterized through overlay of wetlands, hydrography, ownership, zoning, and wildlife data layers. For wetlands to be part of a wildlife corridor, they must have met one or more of the following criteria: (1) located within or contiguous to federal, state, or county park lands; (2) located within or contiguous to areas designated for long-term commercial forestry production; (3) hydrologically connected to marine or freshwater resources; and/or (4) connected to (1,2 or 3) by a forested corridor. Corridors were also characterized by their degree of current protection.

FUNCTIONAL ASSESSMENT PROCEDURE

The functional assessment procedure (FAP) consisted of eight hydrologic/water quality functions and 10 habitat functions. Wetlands were assigned qualitative probability ratings of high, moderate, or low/none. A technical advisory committee consisting of federal, state, local, and tribal agencies involved in wetland regulation or management met regularly to provide technical input to the project.

Hydrologic/Water Quality Functions

Hydrologic landscape functions assess the effects that wetland hydrology has on the flow and quality of water in the watershed. These include: floodflow desynchronization, streamflow/channel maintenance, groundwater recharge, temperature maintenance, sediment/toxicant/bacterial retention, nutrient removal/ transformation opportunity, and seawater intrusion prevention. Assessment of these functions was largely based on interpretation of the effect of wetland hydrology type on the performance of these functions.

Habitat Functions

The FAP divides wetland habitat functions into three landscape scales—intrinsic (local), regional, and global. Intrinsic habitat refers to the habitat functions that wetlands provide for local fauna that live within

and adjacent to wetlands (i.e., small home ranges). The FAP assessed seven functional indicators of intrinsic functions: habitat diversity, habitat size, significant habitat features (mature forests, snags, islands), plant community value, upland buffer condition, presence of open water, and documented species use.

Regional wetland habitat functions assess a wetland's ability to act as a wildlife movement corridor for species that migrate across the landscape or have large home-range requirements. Assessment of this function is based on how wetlands are related to mapped wildlife migration corridors. For example, wetlands part of or contiguous to an undeveloped forested corridor that connects to a large habitat unit such as forest resource lands or protected public lands would be assessed as having a high regional habitat value. Conversely, wetlands isolated (with no forested corridor) from large habitat blocks or other surface water features would be given a low value.

Global wetland functions assess the functional value of wetlands for waterfowl and anadromous fish that migrate out or through the region and for endangered and threatened species. Assessment was based on documented species use and habitat requirements of such species. For instance, wetlands were assessed as having a high potential for waterfowl migration based on mapped locations of regular concentrations of wintering waterfowl and wetland hydrology types that indicate the presence of surface water during migration.

WETLANDS AND THE HUMAN ENVIRONMENT

Data on zoning, urban growth areas, parcelization, ownership, and existing and proposed roads were overlaid with mapped wetlands. The purpose of these overlays was to identify potential conflicts between wetlands protection and development, and to use this information as a screen for prioritizing wetland education, acquisition, restoration, and enhancement efforts. For example, the parcel overlay identifies lots created before local wetland regulations that contain no non-wetland building sites.

DISCUSSION

The GIS procedure resulted in the creation of a computer-based wetlands database that contained data on wetland locations, existing conditions, hydrology, habitat, and relationship to other existing and proposed land-use patterns. This database allows county staff to retrieve and display different "themes" of information. For example, maps and data can be produced that show the location and extent of wetlands that initiate streams, have non-native plant communities, provide fish habitat, or are of high value to migratory birds. These "themes" can be produced rapidly and interactively, creating a valuable informational and educational tool for the public, decision makers, scientists, and regulatory agencies.

The FAP was one potential application of the wetland database. It could be re-run with different criteria based on new information or community concerns. Other applications include prioritizing wetlands for acquisition, restoration, and enhancement. A complete report on the GIS-based procedure and guidance for potential applications is expected to be released in late January.

Application of this GIS procedure in other Puget Sound watersheds is possible, since most of the same information used is available in other areas. Based on regional concerns, other areas may require more or less data for characterizing and assessing wetland functions.

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JURISDICTIONAL CONSTRAINTS AND SYSTEM-WIDE PERSPECTIVES: SIMPLIFICATION AND INTEGRATION IN WATERSHED PLANNING

Andrew M. Fischer[1]

WATERSHED MANAGEMENT AND JURISDICTIONAL CONSTRAINTS

Watershed planning in Puget Sound typically transcends existing political boundaries, involving a variety of agencies and groups. The blend of local, state, federal, and tribal agencies, as well as tribal and community programs, forms an elaborate system to manage a watershed's natural resources. The management strategies of these programs vary from technocratic to collaborative approaches and include direct regulation from the federal level, state agency directives, and local citizen planning initiatives (Table 1).

This framework involves a complex maze of regulatory, permitting and reviewing processes often incomprehensible to the public and to local planners. These complexities produce an overloaded system, in which individual interests are often unable to visualize and comprehend their role in a planning process. As the system becomes overloaded, time is not available for quality understanding of all issues and development of a coordinated plan. Furthermore, the current imbalance and mix of types and levels of management tools for addressing resource-specific interests within watersheds interfere with coordinating system-wide efforts. Conflicts arising from a fragmented framework can occur between competing interests, among different levels of government, among different agencies and jurisdictions, and among various industries and interest groups. The examples provided below show that the management tools for watershed planning in Puget Sound are rendered ineffective by regulatory inadequacies and legal issues, are plagued by goal conflicts, and involve lengthy and costly consensus procedures (Table 2).

Regulatory Inadequacies

In Washington state, a number of studies (Kunz et al., 1988; Cooper, 1986; Eliot, 1985) have demonstrated that, at least up until mid-1986, inadequate wetland mitigation planning, follow-up, documentation, monitoring, and enforcement were all contributing to the ineffectiveness of mitigation within the §404 permitting process. Also, studies evaluating the effectiveness of the §404 program of the Clean Water Act indicate program goals are not being met (Rylko and Storm, 1991; Weinman and Kunz, 1994; Blumm and Zaleha, 1989). As a tool for restoration, mitigation requirements have restored only fragmented pieces of habitats, which has not been sufficient to meet the national goal of "no net loss." And despite the past decade of progress in dealing with wetlands protection, improvement of the wetlands delineation manuals, and memoranda of agreement between the Corps of Engineers and Environmental Protection Agency to guide the consideration of mitigation in the §404 permit process, significant loss and degradation of wetlands will continue. The main reason for this is that "many activities that affect wetlands are beyond the reach of the Clean Water Act" (Weinman and Kunz, 1994).[2] In general, lack of coordinated planning among agencies can leave weaknesses in wetland policies and regulations, leading to inadequacies in addressing system-wide concerns.

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[2] The limitations include: 1) only some activities are regulated; 2) only some wetlands are regulated; 3) case-by-case permit programs do not provide for landscape or watershed considerations in designing compensatory mitigation; and 4) attitudes of those undertaking creation and restoration are created by legal requirement rather than a desire to increase wetland resources or provide long-term management objectives.

Table 1. Watershed planning framework

Plans	**Geographic Scope**	**Agency**	**Problems to Address**	**Focus**	**Actions to Consider**	**Legal Foundation**		
						Federal	State	Local
Non-point Pollution ***Watershed Action Plans***	biogeographic area: watershed	PSWQA and DOE; citizen involvement	non-point pollution: stormwater and CSOs, agriculture practices, on-site sewage, boats and marinas	source control protection	plan including: BMP's, ordinances, permits, education	CWA §319	WAC 400-12; cigarette tax funding	plan using ordinances, agreements
Stormwater ***Basin Plans***	distinctive geographic areas within the comprehensive plan having a unified interest	DOE, cities, and counties	flood zones, aquifer recharge, fish and wildlife habitat, wetlands	technocratic; engineering approach	stormwater facilities, habitat enhancement, sensitive area protection, regulations, source control		GMA; RCW 36.70.330 36.70.340 36.70.350	stormwater utility funds; agency task force
Stormwater Management	political districts: urban cities, counties, municipalities	PSWQA and DOE (administer programs and NPDES permits)	shellfish beds, fish habitat, sediment contamination, water and sediment quality	Control of quantity and quality of water	SWM programs; NPDES permits for watershed; ordinances for erosion control; education; technical assistance; draft legislation (HPA)	CWA §319; NPDES; CZMRA § 6217 (Nonpoint pollution control program)	PSWQA plan, RCW 90.48 (state water quality standards)	stormwater management plan, permits
Development Regulation ***Land Use***	urban, cities, subdistricts	DCD, counties, cities	private land development, roads, other public services	development goals, zoning	zoning ordinances, building and development permits		state statutes	planning and zoning ordinances
Growth Management	political districts: fastest growing counties and cities (stops at HW mark)	local jurisdiction	conservation of resources and protection of critical areas	growth planning	impact fees, sanctions, incentives, grants excise tax		GMA: ESHB 2929	local comprehensive plans
Shoreline Management ***SMP***	federal, tribal, county/city shorelines to 200'	DOE, county and city planning commissions, shoreline hearings board	shoreland development, riparian and floodplain mgt., fish and wildlife habitat protection, public access and recreation	"protection" of shoreland through management of uses.	environmental designations (natural, conservancy, rural, semi-rural, urban); substantial development permits; performance standards	Public Trust, CZMA	SMA (1971), SEPA	Jurisdictional Shoreline Management Master Program
Flood Plain Management	aquatic flood plains	Federal Emergency Management Agency	natural disasters and property damage due to flooding	save lives; protect property, public health, and safety	mitigation, analysis and reevaluation of practical alternatives, building codes and development setbacks	FEMA	Floodplain Management Program, RCW 86.24	County Community Development Departments

Table 1. continued

Plans	Geographic Scope	Agency	Problems to Address	Focus	Actions to Consider	Legal Foundation		
						Federal	State	Local
Hazardous Substances ***Sediment Remediation***	Superfund sites, RCRA- hazmat from current industrial operations	EPA, DOE, NOAA, USCG	contaminated sediments, liability assess and course of remedial action, treatment and storage permits (RCRA)	liability for damage (CERCLA), current waste (RCRA)	capping, dredging, disposal, treatment (CERCLA); permitting waste (RCRA)	RCRA, CERCLA, NRDA, OPA, NCP	Model Toxic Control Act (MTCA)	
Habitat Restoration ***404 Mitigation***	404-development site specific mitigation projects	EPA (CWA §404), CORP (RHA §10), DOE (SMP), DOT	wetlands loss (10/404), habitat protection (local SMP)	avoid, minimize, compensate wetland development for no-net loss;	enhancement, creation, mitigation of habitat	CWA §404, RHA §10, CZMA, NEPA	SMP designation of critical and sensitive areas, SEPA (protect)	local SMPs, volunteer DOE/ King County Wetlands Protection Program
NRDA	NRDA settlements	NOAA	damage assessment and restoration (NRDA)	natural resource trust	damage assessment and restoration	natural resource damage assessment regulations	identified state trustees	identified municipal and local trustees
Endangered Species Act	endangered species habitat	USFW, WDFW, DNR	recovery and survival of endangered and threatened species	species survival in conflict with development projects or other forms of economic activity	aquatic land acquisition, native species transplants	ESA (Habitat Recovery Plans)	Priority Habitat and Species Program (DNR & WDFW)	
Tribal Resources Protection	Usual and Accustomed Fishing Ground	Tribe and Tribal Council (the tribe's decision-making body)	fishing access, habitat loss and water quality degradation	preserve and develop habitat and protect treaty rights	enhance quality and quantity of salmon and shellfish resources and their habitat	federal treaties (e.g. Point Elliott and Medicine Creek)	US v. Washington (384 F Supp. 212) "The Boldt Decision"	

Table 2. Illustrative jurisdictional constraints

Problem type	Example Constraint	Legislation	Problem Description
Regulatory Inadequacies	§404 wetland mitigation	§404 CWA, §10 RHA	Inadequate monitoring and geographic scope
Legal Issues *Regulatory Programs*	Shoreline Management Master Program	SMA	Property rights exemption diminish public trust goal
Constitutional Rights	Dolan v. Tigard Lucas v. South Carolina	Takings Clause of the 5th Amendment	Interferes with state and local efforts to plan for community-wide interests
Goal Conflicts	Tribal Fisheries and Growth Management Act	US v Washington (384 F Supp. 212) and ESHB 2929	Conflicting interests interfere with project goals
Agency Coordination	Elliott Bay/Duwamish Restoration Program	NRDA	Time consuming consensus building

Legal Issues

Property exemptions and constitutional rights issues present constraints to the adoption of a system-wide perspective in watershed planning. The single family residence exemption under the Shoreline Management Act (SMA) reflects a populist notion of fewer constraints on individuals. Single-family residences and normal appurtenances costing less than $2,500 in fair market value are exempt from the Shoreline Substantial Development permit requirement.

This exemption conflicts with the tenet that "coordinated planning is necessary in order to protect the public interest associated with the shorelines of the state while, at the same time, recognizing and protecting private property rights consistent with the public interest" (RCW 90.58.020). The exemptions that apply to single-family residential development have resulted in a substantially altered natural environment and development activities that frequently conflict with the Public Trust Doctrine and the goals of the Shoreline Master Program (SMP) (Lambert, 1993). Lambert (1993) found that the proliferation of docks and other overwater structures, hardening of the shoreline with bulkheads, overwater construction, and runoff associated with single-family home development have adversely affected the public's ability to navigate, swim, and fish and have adversely affected water quality and fisheries habitat.[3]

Constitutional rights as expressed through Supreme Court decisions have broadened property rights in recent years by determining that city or state land use requirements of private property constitute a "takings" and are barred by the constitution. In ***Dolan v. Tigard*** (114 S. Ct. 2309, 1994) the city of Tigard, Oregon, sought compensation for the expansion of a plumbing supply store. The city was willing to grant the permit for expansion on the condition that Mrs. Dolan give the municipality 10 percent of her 1.67-acre lot so that part of it beside a creek could be used as open space and a bike path, and so that a storm drain channel could be constructed. The Supreme Court ruled that such conditions were an unconstitutional deprivation of her property and, in setting a new standard, said cities must show that the

[3] This illustrates that numerous individual decisions on shoreline development can have an aggregate effect on the resource that is the same as if one major decision had been made to destroy the resource (Rieser, 1991).

land request "is related both in nature and extent to the impact of the proposed development." In another case, ***Lucas v. South Carolina*** (112 S. Ct. 2886, 1992), the state setback requirement for construction on barrier islands was also found to be a takings of the full beneficial use of the private property. By elevating property rights, the court has given the judiciary greater freedom to interfere with state and local regulations that control land development in environmentally sensitive areas. Municipalities and states, which increasingly have been seeking land concessions as ways to solve environmental and recreational needs, may find it increasingly difficult to plan for system-wide watershed protection and restoration given these rulings.

Goal Conflicts

Mismanagement of watershed resources and ineffective planning have been evident in the watersheds of Puget Sound. Continued growth and development in the watersheds have placed additional stress on fisheries resources. Some attempts to restore degraded fish runs by the Muckleshoot Indian Tribe have met with failure (Stevens, 1993). Disagreements among the various watershed users (primarily, fishing and recreation vs. development interest) make restoration a very time-consuming and heated process (MIT, 1993). For example, housing developments may not be coordinated with tribal salmonid watershed restoration efforts, which may result in the destruction of stream characteristics, leading to increased stormwater runoff, erosion, and flooding (MIT, 1993).

Efforts to coordinate the restoration efforts with land use and growth management of the region have resulted in disadvantages for both development and fishery restoration interests. Residential development and road construction in the stream corridor have increased turbidity in the water and have clogged the hatchery water drains, flooding some homes (Coccoli, 1993). Local government perceived that the housing needs of one local community cannot always be dealt with through strictly local solutions, because one community's quick, inexpensive, and inadequate solutions seem to impose burdens on other community interests (Baxter, 1974).

Agency Coordination

The coordination of restoration efforts can also present obstacles to system-wide planning. This was the case in the Elliott Bay/Duwamish Restoration Program (EB/DRP). Injuries to natural resources in Elliott Bay from the release of chemical and hazardous substances by the city of Seattle's sewer system were identified by its natural resources trustees, the Muckleshoot Indian Tribe, the Suquamish Tribe, the U.S. Fish and Wildlife Service, the Department of Ecology (DOE) and the National Oceanic and Atmospheric Administration (NOAA). A consent decree settlement required the Municipality of Metropolitan Seattle (METRO) and the City of Seattle to supply $24 million for the restoration of these resources and to create a panel to oversee and manage the implementation of the settlement. Representatives of several other organizations were brought in to provide expertise and knowledge for planning this project. Francisco and Clark (1994) identified many coordination problems that had to be overcome. First, they were faced with the problem of establishing a consensus process for implementing the settlement. This process took nearly a year to accomplish. Second, the process is complicated by diverse points of view that must be considered in the production of informational materials for this purpose. Third, local governments may view the resource from a more direct local service perspective, rather than from the resource-based perspective of most trustees. For example, they may favor corrective projects that include a public education facility, or a public recreation element, even if this would be at odds with some of the habitat value. Finally, consideration and resolution of differing views add to the time and expense of the restoration effort and mean that compromises must be made in order to proceed. Though restoration in this case has laudable goals, coordination across multiple jurisdictions and system-wide interests is costly.

Some constraints within the current watershed planning framework have been illustrated above. The causes of these constraints are several. First, limited laws are applied to new problems year-by-year resulting in an overloaded regulatory process with a plethora of regulations aimed at providing quick solutions to specific problems. These quick solutions inadequately address the consequences and impacts

of interrelated environmental, social, and economic issues. Second, watershed planning is conducted through a technocratic approach, with scientists and engineers in charge. This approach often provides simple myopic solutions to complex, integrated problems. Third, in a tight legal and budget structure, agencies have little flexibility and are under pressure from the legislature and the judiciary, allowing them little room to implement innovative system-wide approaches.

In Puget Sound simplification and integration of the watershed planning framework must first be achieved so that a system-wide planning perspective can follow. Simplification refers to simplified administrative procedures and to simplified data collection and planning techniques adapted to regional manpower and issues and to localized decision-making. Such a system requires simplification so that planning options are clear, accessible, and comprehensible. Integration refers to restructuring to provide for more effective collaboration in planning for protection and restoration of watershed resources. "Policy is integrated to the extent that it recognizes its consequences as decision premises, aggregates them into an overall evaluation, and penetrates all policy levels and all government agencies involved in its execution" (Underdal, 1980).

THE JURISDICTIONAL RESTORATION PLANNING MODEL: STEPS TOWARD SIMPLIFICATION AND INTEGRATION

The Jurisdictional Restoration Planning (JRP) model (Fischer, 1994), a component of the Liberty Bay Restoration Planning Model (RPM) (WSG, 1992) and the Liberty Bay Project, begins to address the simplification and integration of jurisdictional constraints within Puget Sound's watershed planning framework.

The JRP model consists of a map, a database and an evaluative matrix. The jurisdictional map displays sets of jurisdictional information (boundaries) throughout the Liberty Bay watershed in Kitsap County, as well as the boundaries of overlapping jurisdictional associations. These sets of information are also referred to as Jurisdictional Landscape Units (JLU). This map is linked to a database, which provides a detailed description of the JLUs, such as a description of each jurisdiction's legal foundation, relevant statutes, planning procedures, and other appropriate reference material. The map is also linked to a matrix in which relative values are assigned to sets of jurisdictional criteria to determine the jurisdictional feasibility of restoration within JLUs. Through the process of assigning values, integration is achieved across multiple jurisdictions. Values for a set of JLUs can than be overlaid with other component maps or sets of values. Through this process integration can be achieved across multiple components within a watershed.

Simplification

Simplification is achieved through the JRP model by providing a medium of information-sharing and clarified management roles. Centralized information about jurisdictions in one information system can more easily alert users to the problems associated with regulatory inadequacies, as well as identify goal conflicts and the other constraints.

Efficient access to and use of jurisdictional planning information, through the JRP model, can simplify localized administrative and planning procedures. The JRP model serves as a centralized medium where jurisdictional information can be comprehensively ordered and jurisdictional political activity can be closely monitored by all actors or sectors within a watershed. The comprehensive display of a diverse arrangement of jurisdictions makes the process of coordination and goal conflicts among all components of a system become evident. With this evident, it is simpler to avoid delays and duplication of effort in mounting a governmental response to watershed planning efforts. Duplication can easily be identified in areas of overlap within JLUs, as well as easily referenced and resolved.

At the same time, the JRP model, as adapted to watershed or regional issues, fosters an atmosphere of information-sharing and clarified management roles. Organization of information at the regional level presents greater opportunity for jurisdictions with responsibilities in various sectors affecting the region to cooperate and solve problems. In such a situation jurisdictional myopia can be circumvented and

cooperative approaches to restoration planning can begin to be understood. These improvements may reveal new management strategies and suggest new institutional arrangements.

Integration

Integration in watershed planning can only be realized if regulatory and management policies across multiple sectors are aligned to represent regional or system-wide interests. The JRP model addresses these issues of integration through a dynamic, thematic planning process of assigning values to jurisdictional sets of information or JLUs within the watershed, and then overlaying these values with other sets of information or values (Fischer, 1994). Through such a process integration can be achieved both within the jurisdictional component and across multiple components of the watershed.

Integration among jurisdictions within a watershed can be achieved by assigning values to and prioritizing sets of jurisdictional information or JLUs. In the JRP model, criteria of JLUs are rated based on a consensus building or dispute resolution process to determine certain thematic trends. The JLUs can then be ranked and prioritized and displayed on a map. Developing common values across multiple and diverse jurisdictions allows individual actors to consider their role in the region or community. In other words, the JRP model establishes prioritized JLUs across jurisdictional sectors to develop regional themes that represent common regional policies, interests and similar management themes.

Similarly, the RPM can assist in achieving integration across multiple components within a watershed. Other component maps (e.g., parcel market value) whose areas are ranked and prioritized according to thematic values can be overlaid with prioritized JLUs to determine accumulations or combinations of certain thematic patterns throughout the watershed. Such an analysis can be conducted for multiple components or levels of information as the need for comprehensiveness in area-wide planning varies. Also, as regional values and interests are modified, as the watersheds' physical properties change, or as the regulatory policies evolve, they can be incorporated into the rating process. This allows planners and managers to monitor the impacts of system-wide decisions across comprehensive sets of information, to assess coordination possibilities, and to develop more comprehensive and effective management techniques.

As we begin to understand how to identify jurisdictional constraints through an information system, and to resolve them by integrating various components of information, we can begin to understand how the pluralistic nature of jurisdictions can accommodate a system-wide perspective in the management of watersheds. Federal, state, local, and tribal agencies and programs will be able to coordinate the elaborate jurisdictional framework and reduce conflicts and inadequacies arising from a fragmented and overloaded system. Accordingly, more coordinated and effective approaches to management, adapted to regional needs and capabilities, will result.

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INFORMATION SYSTEM OR DATABASE? THE SUCCESS AND FAILURE OF AUTOMATING THE PUGET SOUND ENVIRONMENTAL ATLAS

Elizabeth L. Lanzer[1]

During 1990, 1991 and 1992, the Department of Natural Resources and the Puget Sound Water Quality Authority cooperatively developed a geographic information (GIS) format database containing updated information based on the information presented in the 1987 Puget Sound Environmental Atlas. This database was used to publish the Puget Sound Environmental Atlas 1992 Update, and was intended to be the seed data for the "Puget Sound Geographic Information System." During the past two years, the database has been maintained and some themes updated. It has been distributed to several state and local agencies, and generally successfully managed as a spatial database. A full information system generally includes hardware, software, data, people and procedures crafted together for providing well-defined information needs. The challenge from this point will be to develop support for and to implement the missing components in order to move the Puget Sound Environmental Atlas database into a full information system.

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PUGET SOUND RESEARCH '95

SESSION 2C

CENTRAL PUGET SOUND SEDIMENTS

Session Chair:

John Dohrmann
Puget Sound Water Quality Authority Staff

MONITORING AT TWO SEDIMENT CAPS IN ELLIOTT BAY

Pat Romberg, Craig Homan and Dean Wilson[1]

Since 1990, the King County Department of Metropolitan Services (Metro) has been monitoring two sediment remediation projects in Elliott Bay. Both projects involved "capping" (covering contaminated bottom sediments with a layer of clean sand). In 1990 Metro sponsored the Denny Way sediment cap project, and in 1992, the City of Seattle sponsored the Pier 53-55 sediment cap and enhanced natural recovery area project. Both projects were undertaken in cooperation with the U.S. Army Corps of Engineers (the Corps). The Elliott Bay/Duwamish Restoration Program Panel adopted the Pier 53-55 project in 1993 and is sponsoring the monitoring program. This paper summarizes monitoring methods, results, and discussions of the Denny Way and Pier 53-55 sediment remediation projects.

SUMMARY

The Denny Way and Pier 53-55 monitoring studies have shown that capping and enhanced natural recovery are economical and effective methods for remediating contaminated bottom sediments. Capping proved to be the least expensive active remediation alternative for both projects. Cap thickness measurements have shown that the caps are stable and no erosion is occurring at either project site. Core samples from within the caps have shown that the sediment caps effectively isolate contaminated bottom sediments. Benthic taxonomy data have shown that the caps are being recolonized rapidly. Surface samples from Denny Way have shown that while recontamination is occurring on the cap in front of the largest combined sewer overflow in Puget Sound, it is gradual and is not likely to exceed the state sediment standards within 10 years. Surface samples from the Pier 53-55 area have shown that construction activities nearby caused the recontamination of the remediation area. These results have shown that construction activities in the marine environment are a serious contamination threat to all areas near construction zones. Monitoring results from these studies have also helped the planning effort for other recent capping projects including the Eagle Harbor Superfund site in 1993 and the thin-layer cap at Piers 64 and 65 along Seattle's downtown waterfront in 1994.

BACKGROUND

The Denny Way sediment cap project was conducted as a demonstration of the possibilities for remediating contaminated sediments by capping them with a layer of clean sediment. The project area is located just offshore of the Denny Way combined sewer overflow (CSO) at the foot of Denny Way at the north end of Seattle's downtown waterfront. The project covered 3 acres of contaminated bottom sediments with a 3-foot-thick layer of clean sand. A total of 20,000 yd^3 (15,200 m^3) was delivered and placed at the project location. Metro monitored conditions at the sediment cap in 1990, 1991, 1992, and 1994. Several papers and a draft monitoring report have been published (Sumeri and Romberg, 1991; Romberg and Sumeri, 1991; Metro, 1994).

The Pier 53-55 sediment cap and enhanced natural recovery area are located just offshore of Piers 53, 54, and 55 on the waterfront in downtown Seattle. The site is in front of the city's CSO at the foot of Madison Street. The Pier 53–55 project involved both a 3-foot-thick sediment cap and a 1-foot-thick or enhanced natural recovery area (ENR). The 3-foot-thick sediment cap covers approximately 2.9 acres and was placed on the portion of the remediation site lying in relatively deep water. The ENR was placed on a shallower 1.6-acre area to the northeast. Metro monitored conditions at the remediation site in 1992 and 1993. One report was issued in 1993.

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Both the Denny Way and Pier 53-55 projects involved remediating contaminated sediments located near historical outfalls that discharged untreated sewage. The flows from these outfalls were diverted to the West Point Treatment Plant in 1969 via the newly constructed Elliott Bay Interceptor pipeline. At that time, both outfalls were converted to CSOs, which are relief points for the Elliott Bay Interceptor. If wastewater flows going into the interceptor exceed its capacity, the excess will be diverted through a CSO and into Elliott Bay.

Because of the historical and current discharges at both sites, organic and metal contaminants have accumulated in the sediments. Several sediment monitoring studies have identified the Seattle waterfront as a problem spot because of elevated levels of toxic chemicals in bottom sediments (Malins et al., 1980; Romberg et al., 1984; Tetra Tech, Inc., 1988; Metro, 1988, 1989). Because of the conclusions of these studies, both the Denny Way and the Pier 53-55 sites were considered for remediation.

Source Control

Source control at both the Denny Way and Pier 53-55 sites began with the diversion of continuous untreated wastewater flows to the West Point Treatment Plant in 1969. In addition, Metro has reduced the toxicant loading from CSOs at Denny Way through education programs and permit requirements aimed at reducing the amounts of toxic chemicals entering the wastewater system. The City of Seattle has reduced discharges from the Madison Street CSO at the Pier 53-55 site to no more than one overflow event per year.

Selection of Remediation Methods

After source control was addressed, cooperating agencies considered several possible methods for remediating the contaminated sediments, including natural recovery; dredging with both nearshore-confined-aquatic disposal and upland-confined disposal; and sediment capping. For both project sites, it was agreed that sediment capping was the best alternative. An active remediation method was selected because natural recovery, or allowing new clean sediments to accumulate naturally, would take 20 to 60 years along the waterfront (Metro, 1987). Dredging was not chosen because of its expense and the lack of disposal sites. Additionally, conventional dredging and disposal equipment can be used in the capping process, and, at these two project sites, the added expense of placing sand using a clamshell crane was not necessary. Coordination with waterway maintenance dredging reduced costs further and was a beneficial use of clean dredged material.

Sediment Cap. A sediment cap is a layer of clean sediment placed on the marine floor, isolating contaminated bottom sediments and providing a clean substrate for marine life. To insure long-term isolation of contaminants, the cap material should have minimal porosity and be thick enough so that benthic organisms do not burrow through the cap. Three feet is considered thick enough for inshore areas of Elliott Bay.

Enhanced Natural Recovery. Sediment capping has been effective at isolating contaminants, but the thickness of a sediment cap has caused a concern about navigational depths in capped areas. This concern has led to the use of a thin-layer cap (1 ft or 30 cm thick) for remediating areas in shallow water. A thin-layer cap is called "enhanced natural recovery" to distinguish it from a thicker sediment cap because the thinner cap possibly will not isolate underlying sediments. Enhanced natural recovery is intended to provide a clean substrate for marine life, cause minimal reduction in navigational depth, and provide preliminary data on the feasibility of this type of remediation.

Natural recovery occurs, first, when contaminants degrade naturally through oxidation or other degradation processes, and, second, when enough new clean sediment is deposited to cover the contaminants and reduce chemical concentrations through a natural capping process and dilution.

Enhanced natural recovery may speed up both components of natural recovery. It is anticipated that the thin layer of clean sediment will initially isolate the contaminated sediments. Then when bioturbation occurs, chemical contaminants are brought up into the oxygenated surface sediments. Chemicals that will

break down, such as organics, will degrade by oxidation and other processes, and chemicals that do not break down, such as metals, will be dispersed among the clean sediments and be reduced in concentration.

METHODS

Before capping, a sediment placement plan was developed and stakes for measuring cap thickness were installed. After capping, coring stations, surface grab stations, and benthic grab stations were sampled (see Figures 1 and 2).

Cap Placement

The Corps and its contractor placed the sediment layers at both the Denny Way and Pier 53-55 sites using a bottom-dump barge. A bottom-dump barge deposits dredge material through bottom-opening doors. The doors were opened slowly while the barge was maneuvered by tugboats. The sediment was slowly placed on the marine bottom to minimize bottom disturbance. A computerized survey system with visual display guided the tugboat operators to the desired location. The placement process was to spread a thin layer of sand, about 6 inches (15 cm) thick, with each barge pass and use multiple barge passes to achieve the desired cap thickness.

Before the caps were placed, the capping areas were divided into barge tracks. Barge tracks are the area where one entire barge-load of sand would be spread. The shape and size of the barge tracks were designed to accommodate length of the barge used, area covered, and thickness of the material deposited. Material for both projects came from the Duwamish River, where the Corps dredged clean sand during scheduled maintenance of the navigable waterway.

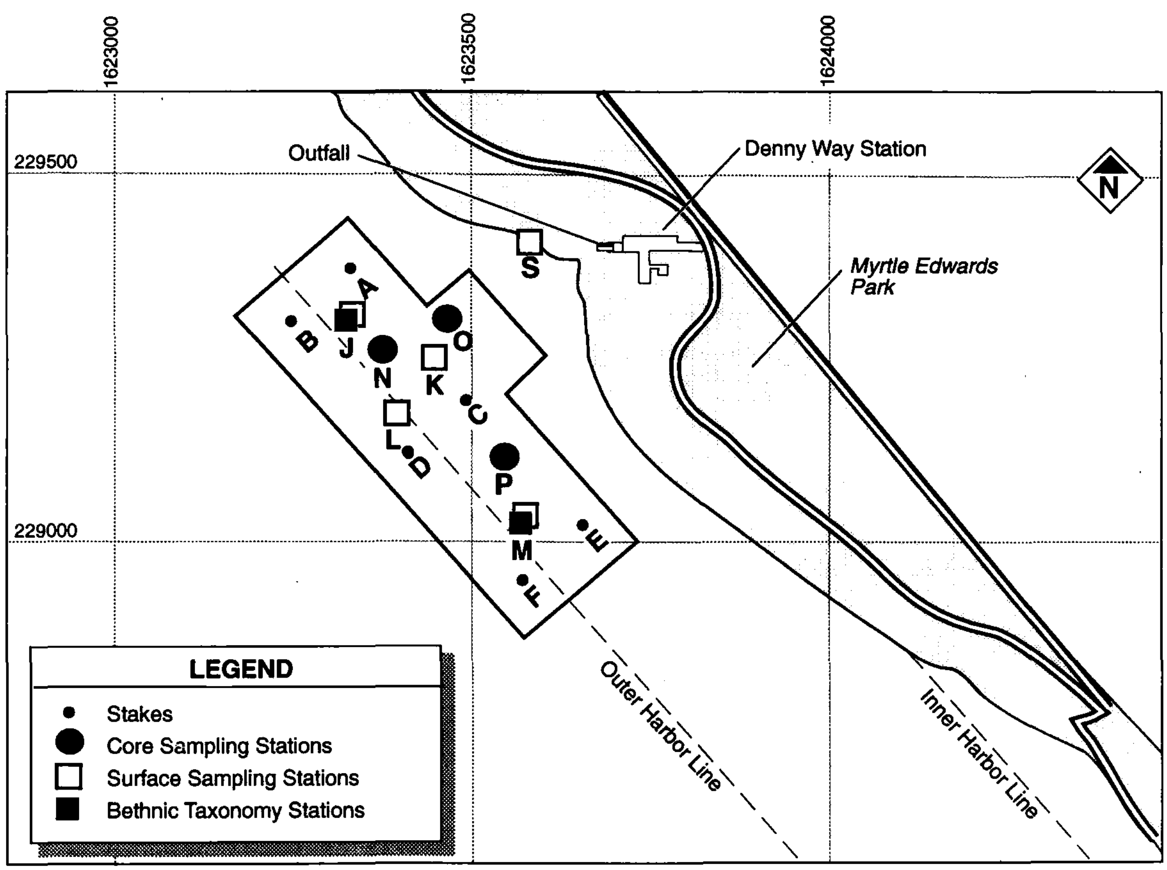

Figure 1. Denny Way Sampling Stations

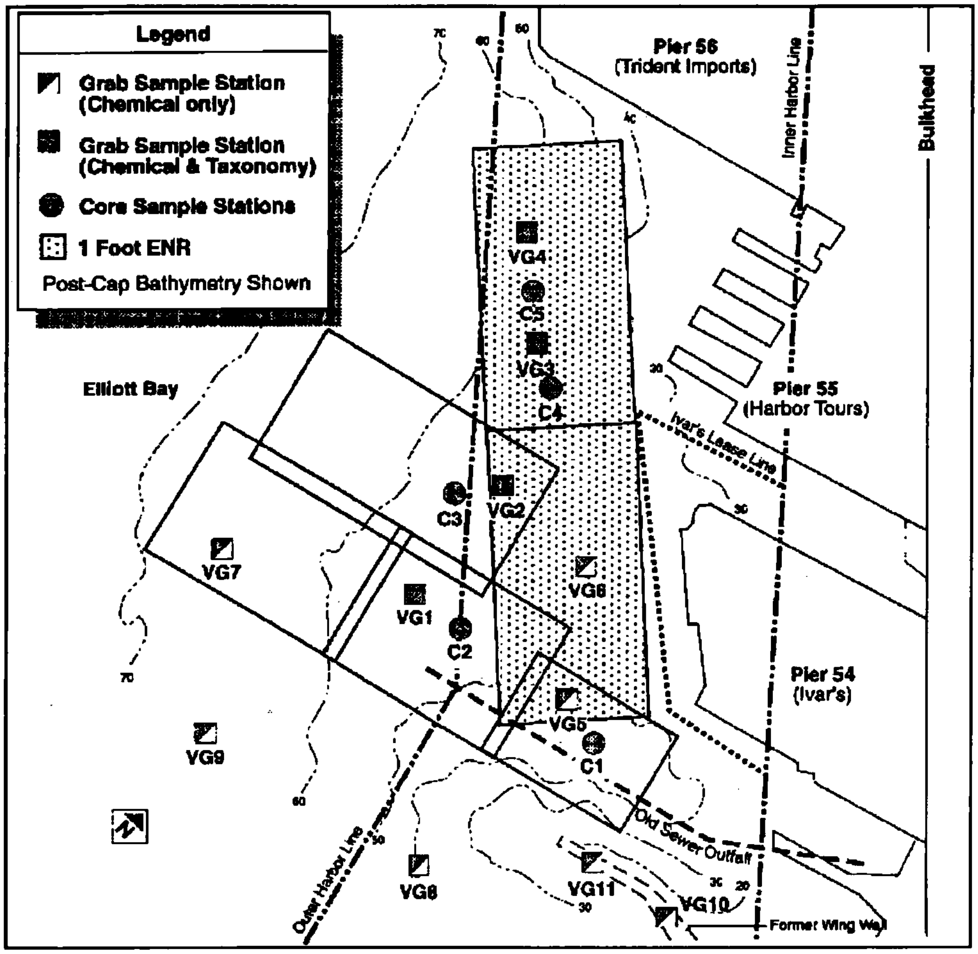

Figure 2. Pier 53-55 sampling stations

Metro conducted chemical analyses of the river sediments before they were dredged, verifying their suitability for use either as capping material or for disposal at the clean-dredged-material disposal site in Elliott Bay.

Cap Thickness and Stability

Cap thickness and stability over time were measured at both sites using measuring stakes that were installed before the caps were placed. The measuring stakes are 13- to 18-foot-long (3.9 to 5.5 m), 1 inch diameter (2.5 cm) steel pipes. A scuba diver pounded the steel stakes into the bottom, leaving 4.7 to 4.8 feet (1.42 to 1.45 m) exposed above the bottom. A scuba diver measured the stake height with a surveyor's rod before and during cap construction to guide cap placement and after cap placement and each monitoring year to check for erosion.

Core Chemistry

Sediment cores were collected to determine if contaminants are migrating from underlying sediments up into the cap. Core sampling methods were similar for both projects. A diver collected the core samples using a pneumatic jackhammer to drive a 6-foot-long (1.8 m), 4-inch-diameter (10 cm), thin-walled-aluminum coring tube through the cap and at least 6 inches (15 cm) into the underlying contaminated

sediments. Cores were divided into five 6-inch-long (15 cm) vertical samples—four from within the cap and one from below the cap. The samples were analyzed for trace metal, organic, and conventional parameters. Three coring stations were sampled at Denny Way in 1990, 1991, 1992, and 1994. Four coring stations were sampled at Pier 53-55 in 1992 and 1993.

Surface Chemistry

Surface sediment sampling methods were similar for both projects. Subtidal sediments were collected with a 0.1-m^2 Van Veen grab sampler. When possible, three individual grabs were taken at each station. A 2-cm-deep subsample was taken from the top of each grab and composited into one sample. The samples were analyzed for trace metal, organic, and conventional parameters. At Denny Way, four on-cap surface stations (J, K, L, M) were sampled in 1990, 1991, 1992, and 1994. At Pier 53-55, seven surface stations (VG1 through VG7) were sampled within the remediation area in both 1992 and 1993. Outside the remediation area, four stations were sampled along the southern boundary—two (VG8 and VG9) were sampled in 1992 and three (VG8, VG10, and VG11) were sampled in 1993.

Benthic Recolonization

Subtidal sediment samples, used to analyze the benthic taxonomy at both project sites, were collected with a 0.1 m^2 Van Veen grab sampler. Five replicate samples were taken at every station. The benthic samples at both sites were collected in August to reflect the period of highest abundance. First-year samples were collected five months after cap placement. Taxonomic analysis was conducted by Marine Taxonomic Services.

At Denny Way, benthic taxonomy samples were taken at Stations J and M in 1990, 1991, 1992, and 1994. At Pier 53-55, benthic taxonomy samples were taken at VG1 and VG2 from the 3-foot cap and VG3 and VG4 from the ENR in 1992 and 1993.

RESULTS AND DISCUSSION

Cap Placement, Thickness and Stability

Denny Way. At Denny Way, cap thickness measuring stakes were monitored before, during, and after cap placement. Stake measurements, taken after the cap was placed, showed that the cap is 3 feet thick (90 cm) over about half of the capping area. The cap is slightly less than 3 feet thick over about a quarter of the area, and is only 1.5 feet (45 cm) thick in places over the other quarter of the area.

The project plan at Denny Way was to create a cap 3 feet thick over the approximate 3 acre capping area. During cap placement, 13 barge loads or 20,000 yd^3 (15,200 m^3) of clean sand were spread. This represents about 25 percent more sand than was calculated as necessary for covering an area this size. The reasons for the sand loss appeared to be a north-northwesterly current during placement and the fact that the barge tracks, or the area over which one barge-load of sand was placed, were too large. At Denny Way, some barge tracks were 600 feet long, which made it difficult for the tugboat operators to spread sand uniformly along the entire barge track. The longer barge tracks also required frequent reversing of direction which directed propwash at the barge, causing further dispersal of sand.

In the years after cap placement at Denny Way, the average cap thickness changed a small amount ranging from 0.05 to 0.1 foot (1.5 cm to 3 cm). The largest change at a single stake was 0.2 foot (6 cm) during the first year after capping. In the last couple years of monitoring, however, stake measurements have been nearly unchanged indicating the cap is stable and there are no signs of erosion.

Pier 53-55. As a result of the sand loss at the Denny Way project, the Pier 53-55 barge tracks were shortened to about 300 feet, giving the tugboat operators more control. Also at Pier 53-55, the Corps required a study of the local currents and then used the information when placing the capping sand. Both adjustments resulted in much less sand loss at Pier 53-55. At Pier 53-55, stake measurements taken after the cap was placed showed that the actual thicknesses of the cap and ENR were very close to the planned thicknesses. The 3-foot cap ranged from 2.5 to 3.5 feet (75 to 105 cm) thick, and the 1-foot ENR ranged from 0.8 to 2.1 feet (30 to 64 cm) thick. The 3-foot cap and the 1-foot ENR were created using 10 barge

loads or 22,000 yd^3 (16,700 m^3) of clean sand, which was the amount calculated for the project. While some sediment drifted from some barge tracks onto adjacent ones, the overall amount of sediment drift was minimal. Also, a minimal amount of sediment drifted off the project site.

Measurements taken in 1993 showed mostly minor thickness changes in the range of a few hundredths of a foot. Four measured changes were equal to or slightly greater than 0.1 foot (3 cm) and one measurement indicated that the cap was over 0.5 foot (15 cm) thicker. The extra sediment may have been deposited by construction activities at the downtown Seattle ferry terminal. Overall, the measurements show that the cap and ENR are stable and show no signs of erosion.

Core Chemistry

Core samples taken in 1990, 1991, 1992, and 1994 at Denny Way and in 1992 and 1993 at Pier 53-55 showed that the concentrations of metals and organics were low and nearly uniform throughout the capping sediment at both sites. A consistent and sharp contrast between the capping sediments and the contaminated underlying sediments showed that there are no chemicals migrating up into the capping sediments from below at either site.

SURFACE CHEMISTRY

Denny Way. At Denny Way, surface sediment studies conducted between 1990 and 1994 showed that the number of chemicals and concentrations are increasing gradually. In 1994, most chemical parameters in the top 2-cm of the capping sand, however, were less than 50 percent of the state sediment quality standards (SQS) and less than 15 percent of the state cleanup screening levels (CSL).

The 1990 baseline study showed that the cap surface was clean and very much like the within-cap core samples. Five PAHs and eleven metals were found in all four cap surface samples. Three additional PAHs and two other additional organic compounds were found in at least two cap samples. There was little if any spatial variation; the southernmost station (M) had the fewest detected chemicals and the lowest concentrations while the other three were essentially identical. All concentrations were well below the SQS.

The second study in 1991, one year after cap placement, showed that the number of detected compounds and the concentrations of previously detected compounds increased at all the on-cap stations. At least nine PAHs were detected in the 1991 surface samples, compared to five PAHs found in 1990. The average concentration of previously detected PAHs increased two to eight times. Average metal concentrations increased at slower rates than the PAHs. Silver was detected at the three northern sites. Trace amounts of one polychlorinated biphenyl (PCB) appeared at each of the four on-cap sites. Pesticides and volatile organics remained absent. The station located closest to the shore and closest to the outfall (K) had the highest concentrations and the most compounds detected.

In 1992, two years after cap placement, concentrations and the number of parameters detected continued to rise. At least 12 PAHs were detected at each station, up from nine the year before. Three more metals, cadmium, antimony, and thallium, were detected for the first time at all four stations. At the southernmost station, PAH concentrations rose more than they had between 1990 and 1991. Rates of PAH increases at the other three stations were lower than the previous year. Lead, mercury, and silver were the only metals to increase noticeably. The station located closest to the shore and closest to the outfall continued to have the highest concentrations and the most compounds detected.

Two surface samples that were taken from on the cap after a CSO discharge during low tide scoured nearshore and intertidal contaminated sediments in the fall of 1992 showed that the discharge did not cause any detectable additional recontamination of the cap. Concentrations were unchanged or lower at one station and the other station did not appear to be significantly affected.

In 1994, four years after cap placement, the number of compounds detected at each station leveled off while the concentrations of detected chemicals continued to increase. At least 10 PAHs were detected at each station on the cap compared to 12 in 1992. One PCB was detected in trace amounts at three of the four on-cap stations. A volatile compound (acetone) and a pesticide (4,4'-DDD) were detected in trace

amounts on the cap for the first time. The station nearest to the shore and outfall again showed the highest concentrations of all on-cap stations. At this station (K) and the station just offshore from it (L), cadmium, copper, lead, chromium, mercury, silver, and zinc all showed increases and PAHs increased at a faster rate in 1994 than in 1992. The station to the north (J) and the station to the south (M) showed no significant changes for PAHs or metals.

The four replicate samples taken at the station with the highest concentrations showed that total LPAHs ranged from 15 to 29 percent of the SQS and from 7 to 14 percent of the CSL. HPAHs ranged from 32 to 46 percent of the SQS and from 6 to 8 percent of the CSL. Mercury ranged from 36 to 73 percent of the SQS and from 25 to 50 percent of the CSL. Zinc ranged from 13 to 22 percent of the SQS and from 6 to 10 percent of the CSL. All other detected sediment management standard metals were approximately 10 percent of the SQS.

The contamination found on the Denny Way cap surface 1, 2, and 4 years after capping is presumably present in a layer of fine material that has accumulated on the surface of the cap. The two potential sources of the contaminated fine sediments were solids discharged from the Denny Way CSO or contaminated nearshore sediments redistributed onto the cap by storm waves in shallow water. Stormwater samples have been analyzed but not interpreted yet, and additional intertidal and nearshore sites were sampled in 1994 and have not been completely interpreted.

Pier 53-55. At Pier 53-55, surface sediment studies were conducted in 1992—3 months after capping—and in 1993—one year later. The results from the 1993 study showed that the entire remediation site had been recontaminated. The recontamination was likely caused by construction activities at the adjacent downtown Seattle ferry terminal.

1992 Baseline samples

At Pier 53-55, the 1992 baseline surface samples showed that the surface of the remediation area was clean and that chemical concentrations were uniform over the entire area. Organic and metal contaminants, when detected, were in low concentrations and none exceeded the CSL or the SQS.

1993 Sampling observations

During the following year's sampling at the remediation site, the monitoring team discovered visible evidence of creosote contamination in the southeast corner of the study area.

Outside the remediation area

A thick black ooze was found on the surface of the sediments at two stations in the southeast corner of the study area (VG10 and VG11). The ooze had the consistency of mayonnaise and had a very strong coal-tar creosote smell. The samples at one station were filled entirely with the black material. The samples at the other station showed about a 2-in-thick (5 cm) layer of the creosote material over top of sand. After removing the top 0.8-in (2 cm) subsamples, the excess sample material was placed in a 5-gallon (20 L) bucket and then poured back into the water at the station. As the excess material entered the water, it produced an oil slick that covered an area about 10 ft by 20 ft (3 m by 6 m).

Inside the remediation area

Samples taken at the on-cap station closest to where the black ooze was found (VG5) contained small pieces of broken creosote-treated pilings. Obvious pieces of piling were removed from the samples before the subsamples were removed. Oil droplets also appeared on the sediment surface as the water was drained from the samples.

1993 Analytical data

The results of the analysis of the surface samples show that, after only 14 months, the entire 3-foot cap and ENR have been recontaminated and the southeast half of the remediation area exceeds the CSL. The highest chemical concentrations were found outside the remediation area at the two stations in the southeast corner of the study area.

Alongshore to the north and offshore to the west, the concentrations decreased consistently with distance from the southeast corner of the study area. The station on the southeast corner of the 3 foot cap showed the highest chemical concentrations of all stations within the remediation area. Stations in the middle of the remediation area showed lower concentrations and the lowest concentrations were found at the station farthest offshore and the second lowest concentrations were found at the station farthest north.

Chemical concentration comparison between Denny Way and Pier 53-55

Comparing sampling results in mg/kg dry-weight from the Denny Way station with the highest concentrations (Station K) in 1992 (2 years after capping) to the Pier 53-55 station with the highest concentrations (Station VG5) in 1993 (14 months after capping) showed that total LPAHs were 114 times higher and total HPAHs were 34 times higher at Pier 53-55. Comparing total LPAH and HPAH concentrations from Denny Way Station K to the other stations in the Pier 53-55 remediation area showed that concentrations from six of the seven on-cap Pier 53-55 stations were higher than the highest Denny Way values. Only the station farthest offshore on the Pier 53-55 cap had lower concentrations.

Source of Recontamination of the Pier 53-55 Remediation Area. The recontamination of the Pier 53-55 remediation area may have been caused by a few sources, some of which remain unknown without further study. Three possible sources are construction activities at the downtown Seattle ferry terminal, the Madison Street CSO, and wave action redistributing contaminated nearshore sediments.

In the Pier 53-55 area near the stations where black creosote material was found, a wood-piling wing wall was removed a few months prior to sampling. The wing wall was part of the auxiliary ferry terminal loading slip located on the north side of the downtown Seattle ferry terminal. The wall was constructed with about 400 creosote-coated wood pilings. The wood pilings were removed by a contractor hired by the Washington Department of Transportation. The contractor used a crane barge with a clamshell bucket to pull the pilings out of the bay bottom and to dig holes in the bottom to locate broken pilings.

It is not likely that recontamination of the Pier 53-55 remediation area was caused by the Madison Street CSO or wave action redistributing contaminated nearshore sediments. The 1993 Pier 53-55 sediment study has shown a very high ratio of LPAH concentrations compared to HPAH concentrations. If the recontamination came from the Madison Street CSO or nearshore sediments, similar concentration ratios would most likely have also been found on the Denny Way cap and in previous studies of nearshore sediments in the Pier 53-55 area. Studies of the Denny Way sediment cap and of sediments under Piers 54 and 55 (Metro, 1993), however, have shown much lower overall concentrations and lower LPAH concentrations than HPAH concentrations. The high relative LPAH concentrations at the Pier 53-55 site were distinctly different from the sediment chemical makeup at the Denny Way cap and in the sediments inshore of the Pier 53-55 remediation area. The concentrations of organic chemicals are also much lower on the Denny Way cap, even though the Denny Way CSO discharges a much greater volume than the Madison Street CSO and the study duration has been longer at Denny Way than at Pier 53-55.

It is significant that the data from the Pier 53-55 area showed much higher concentrations of LPAHs than other organic compounds. At the stations in the southeast corner of the study area and the station on the southeast corner of the 3-foot cap, LPAHs exceeded the CSLs in 17 cases compared to 5 CSL exceedances for other organic compounds. The LPAHs that exceeded the CSLs were naphthalene, acenapthene, phenanthrene, anthracene, fluorene and 2-methylnaphthalene. All of these are found in coal tar (Merck, 1976).

It is possible that the source of the LPAHs is coal-tar creosote, which is used to coat and protect wood pilings in the marine environment. Up until early 1993, the auxiliary ferry terminal loading ramp wing wall was located about 150 feet south of the station on the southeast corner of the 3 foot cap. During the service life of the wing wall, it is possible that a large amount of creosote sloughed off of its 400 pilings and settled in the sediments at the base of the pilings. When the wing wall was removed, the creosote-contaminated sediments at the base of the pilings were stirred up into the water column and resettled onto a broad area surrounding the wing-wall site. Recent sediment core samples collected for the Washington Department of Transportation near the ferry terminal show elevated PAH concentration that exceeded the

sediment standards from the surface of the bottom sediments down to a sediment depth of 20 feet (6.1 m) (Hart Crowser, 1994).

There is a strong correlation between the demolition of the ferry terminal wing wall, the discovery of coal-tar creosote in the sediment samples, and the results of the sediment chemistry analysis of the samples from the southeast section of the Pier 53-55 study area.

Benthic Recolonization

Denny Way. Three years of benthic data at Denny Way showed that the average number of individuals per sample doubled from 1990 to 1992, and the number of species and biomass steadily increased over the three annual studies. The polychaete taxonomic group was the most abundant, had the greatest number of species, and had the highest biomass. Over the three years, however, the relative dominance of polychaetes was steadily being challenged by the rise in numbers, species, and biomass of crustaceans and mollusks. In 1994, benthic samples were collected but have not yet been interpreted.

The average number of individuals for all species at both stations increased from 417 individuals per replicate sample in 1990 to 572 in 1991 and to 832 in 1992. The total number of species increased and then appeared to level off. The number of species increased from 138 in 1990 to 159 in 1991, then to 160 in 1992. Biomass increased in each of the three years. When both stations sampled are averaged together, biomass increased from 2.3 grams per replicate sample in 1990 to 4.7 grams (factoring out a high replicate sample) in 1991 to 5.4 grams in 1992.

Pier 53-55. At Pier 53-55, a comparison of the 1992 baseline benthic taxonomy study to the 1993 benthic taxonomy study showed that the average number of individuals in each replicate sample at all stations increased by a factor of approximately 4. The number of species increased by 35 percent and the biomass increased by 30 percent.

The average number of individuals for all stations increased from 258 per replicate sample in the baseline study to 923 in 1993. Polychaetes were the most abundant in both years and increased from an average of 177 individuals in the baseline study to 681 in 1993. Mollusks increased from an average of 37 individuals in the baseline study to 148 in 1993, while crustaceans increased from an average of 27 individuals in the baseline study to an average of 40 in 1993.

The total number of species increased from 139 in the baseline study to 215 species in 1993. Polychaetes were the most diverse taxonomic group in both years and increased from 80 species in the baseline study to 123 species in 1993. Mollusks increased from 37 species in the baseline study to 45 in 1993, while crustaceans increased from 27 species in the baseline study to 40 in 1993.

Biomass increased from an average total of 2 grams for all station and all species in the baseline study to 2.9 grams in 1993. Average total biomass for polychaetes remained stable at an average of 1.6 grams for both the baseline and 1993 studies. Mollusk biomass increased from an average of .07 gram in the baseline study to 0.63 gram in 1993, while crustacean biomass increased from an average of 0.11 gram in the baseline study to 0.24 gram in 1993.

Benthic comparison between Denny Way and Pier 53-55

A benthic taxonomy comparison of samples collected 17 months after remediation at both the Denny Way and Pier 53-55 sites showed that many species were present in similar proportions at both sites. The total number of species and the average number of individuals per replicate sample, however, were significantly higher at Pier 53-55, while biomass was significantly higher at Denny Way.

A. multifilis, Lumbrineris sp. indet., and *E. carcharodonta* were among the five most abundant species at both caps. Other species among the most abundant at both caps include *Prionospio steenstrupi, Axinopsida serricata*, and *Spiochaetopterus costarum*. *Capitella capitata*, a known indicator of organic enrichment, was found in greater numbers at Denny Way than at Pier 53-55. *Asabellides lineata*, known for being sensitive to sediment contamination, was found in abundance at Pier 53-55 but was not detected at Denny Way.

CONCLUSIONS

Cap Placement and Thickness

Cap placement

The method used to remediate contaminated sediment at both Denny Way and Pier 53-55 was much less costly than any alternative. Coordination with Corps' waterway maintenance dredging reduced costs further and was a beneficial use of clean dredged material. Conventional dredging and disposal equipment was used in the capping process, and the sediment was deposited directly from a bottom-dump barge, avoiding the expense of sediment placement using a clamshell crane. After the Denny Way capping project, adjustments were made in the capping procedure, which resulted in much less sand loss at Pier 53-55.

Cap thickness

Denny Way. Cap thickness measurements at Denny Way show that cap thickness has changed very little over the years of study and showed that the cap is very stable. Most commonly, the cap has either become thicker or thinner in the hundredths of a foot range. Changes this small are insignificant and were likely a measurement variation rather than an actual change in the thickness of the cap.

Pier 53-55. With the exception of the one stake that had an extra 0.5 foot (15 cm) of sediment, all of the changes in cap thickness were less than a few inches and most were around 0.1 inch (0.25 cm). The differences were minor and show that the cap is stable and functioning to isolate the underlying sediments.

Core Chemistry

Core samples taken in 1990, 1991, 1992, and 1994 at Denny Way and in 1992 and 1993 at Pier 53-55 showed that the concentrations of metals and organics were low and nearly uniform throughout the capping sediment at both remediation sites. A consistent and sharp contrast between the capping sediments and the contaminated underlying sediments showed that there were no chemicals migrating up into the capping sediments from below at either site. These results were consistent with the Corps' confined aquatic disposal and capping project in the lower Duwamish River's west waterway, which showed no migration from the underlying sediments up into the capping sediments after five years of monitoring.

Surface Chemistry

Denny Way. The four studies conducted between 1990 and 1994 showed that the number of chemicals and concentrations increased each year. Most chemical parameters in the top 2 cm of the capping sand, however, were less than 50 percent of the SQS and less than 15 percent of the CSL. The four replicate samples taken at the station closest to shore and closest to the Denny Way CSO in 1994 showed that total LPAHs ranged from 15 to 29 percent of the SQS and from 7 to 14 percent of the CSL. HPAHs ranged from 32 to 46 percent of the SQS and from 6 to 8 percent of the CSL. Mercury ranged from 36 to 73 percent of the SQS and from 25 to 50 percent of the CSL. Zinc ranged from 13 to 22 percent of the SQS and from 6 to 10 percent of the CSL. All other detected sediment management standard metals were approximately 10 percent of the SQS.

Pier 53-55. The results of the analysis of the surface samples show that, after only 14 months, the entire 3-foot cap and ENR have been recontaminated and the southeast half of the remediation area exceeds the state sediment standards. The highest chemical concentrations were found outside the remediation area near a former wing wall, which was removed in early 1993 and was part of the downtown Seattle auxiliary ferry terminal loading ramp. Alongshore to the north and offshore to the west, the concentrations decreased consistently with distance from the former wing-wall site. The lowest concentrations were found at the station farthest offshore, and the second lowest concentrations were found at the station farthest to the north.

There is a strong correlation between the demolition of the ferry terminal wing wall, the discovery of coal-tar creosote in the sediment samples, and the results of the sediment chemistry analysis of the samples from the southeast section of the Pier 53-55 study area.

Benthic Recolonization

Denny Way. Three years of benthic data at Denny Way showed that the average number of individuals per sample doubled from 1990 to 1992, and the number of species and biomass steadily increased over the three annual studies. The polychaete taxonomic group was the most abundant, had the greatest number of species, and had the highest biomass weight. Over the three years, however, the relative dominance of polychaetes was steadily being challenged by the rise in numbers, species, and biomass weight of crustaceans and mollusks.

Pier 53-55. A comparison of the 1992 baseline benthic taxonomy study to the 1993 benthic taxonomy study showed that the average number of individuals in each replicate sample at all stations increased by a factor of approximately 4. The number of species increased by 35 percent and the biomass increased by 30 percent.

Taxonomic comparisons between the Pier 53-55 cap and the Denny Way cap one year after cap placement showed that many species were present in similar proportions at both sites. The total number of species and the average number of individuals per replicate sample, however, were significantly higher at Pier 53-55, while biomass was significantly higher at Denny Way.

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PHYSICAL MONITORING OF SUBTIDAL SEDIMENT CAP CONSTRUCTION AT THE WYCKOFF/EAGLE HARBOR EAST HARBOR OPERABLE UNIT, AND OBSERVATIONS FOLLOWING METHODS OF CAP PLACEMENT

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ABSTRACT

To remediate PAH-contaminated sediments at the East Harbor Operable Unit of the Wyckoff/Eagle Harbor Superfund Site, native sediments were capped with sands from the federal maintenance dredging of the Snohomish River. Cap design and cap placement were performed by the U.S. Army Corps of Engineers, Seattle District. The cap was constructed using both hydraulic wash-off and split-hull placement of dredged sands. Placement goals consisted of depositing dredged sands within a designated cap area to a thickness of 3 feet with little disturbance of native sediments during the placement process. Physical monitoring of cap construction consisted of bathymetric surveys, sediment vertical profile photography (SVPS), towed video and sub-bottom sonar surveys. Goals of the physical monitoring consisted of documenting the areal extent and thickness of cap material placed at the site. Preplacement conditions were documented in terms of bathymetry and substrate characteristics such as grain size, sedimentary or stratigraphic features, and biological communities. Throughout the six-month cap placement period, numerous "condition surveys" consisting of bathymetry and SVPS were conducted and compared to the preplacement conditions in order to determine cap extent and thickness. During a hiatus in cap placement at the fourth month, video surveys were conducted to inspect the surface of the cap for signs of contamination. Immediately following the completion of cap placement, a comprehensive post-placement survey was conducted consisting of bathymetry, SVPS, and sub-bottom sonar surveying.

Data collected during the condition surveys were used to refine construction activities and provided regulatory agencies with snapshots of environmental conditions associated with cap construction. The post-placement survey characterized the final cap deposit, defining both the areal extent of the cap and the thickness of the cap across the placement area. These data indicated that the footprint of cap material mirrored the polygonal shape of the target placement area, extended beyond the target placement area, but was within the predefined circular limit of placement. In addition, cap thicknesses within the placement areas ranged from 0 to 10 feet. Greater than 95 percent of the target area was blanketed with 1 to 4 feet of cap sediment. The thinnest accumulations of cap material were at the high-current area adjacent to the ferry berthing facility, while the thickest accumulations were observed in the northern portion of the placement area, where the placement barges could easily avoid ferry traffic. SVPS results indicated the cap was composed of reduced, medium sands having a high inventory of woody particles. Distinct strata were observable with little or no physical mixing between native and cap sediments. Some infaunal organisms survived cap placement through vertical migration. In the vessel traffic lane, small-scale bedforms were formed on the cap subsequent to deposition. Respectively, SVPS and video surveys indicate that infaunal recolonization is proceeding and that epifaunal colonization has occurred rapidly. Benthic invertebrates and fishes were observed throughout capping activities.

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ELLIOT BAY WATERFRONT RECONTAMINATION STUDY

Dale Norton and Teresa Michelson[1]

ABSTRACT

Our presentation reports the preliminary results of an ongoing study of the Seattle waterfront to identify sources of recontamination to sediments. The study is being conducted on behalf of the Elliot Bay/Duwamish Restoration Program Panel, an interagency/intergovernment group interested in conducting sediment cleanup along the Seattle waterfront. The overall goal of the study is to determine whether sediment cleanup along the waterfront is likely to be successful by identifying rates and components of recontamination that would be expected to occur following cleanup activities. Results of the one-year field component of the study will be presented, including sediment grain size, accumulation rates, sediment trap chemistry, and detailed current meter studies of the waterfront. Discussion will address the bottom and near-surface current speed and direction, influence of piers and vessel prop wash on transport and resuspension of contaminated sediments, and contaminant levels in surface and near-bottom particulates.

These data will ultimately be used in conjunction with source evaluations also being conducted for the study to develop a preliminary conceptual model for the Seattle waterfront. The conceptual model will form the basis for modeling to predict rates of recontamination, and to identify source control and/or remedial actions that have the greatest chance of success.

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TIDALLY INFLUENCED GROUNDWATER INVESTIGATIONS OF THIS CRITICAL TRANSITION ZONE

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INTRODUCTION AND RATIONALE

Within the urban industrial waterfronts of Puget Sound, many of the contaminated sites lie close to the shore and therefore within the range of the tidally influenced groundwater. The 4- to 6-meter range of tides in Puget Sound creates fluctuations in groundwater level up to hundreds of meters inshore, depending on the hydrogeology of the shorelands.

These sites often contain old contamination from a variety of urban and industrial uses. The industrial urban waterfronts are key areas for our economy. These sites are on prime land for port and associated water-dependent, water-related industrial, and commercial development. It is important that we recycle and revitalize our urban industrial core areas rather than moving out of our urban centers, chewing up more raw land and building bigger transportation links to make it work.

In the development process, the environmental and human health concerns of contact with, inhalation of, and ingestion of contaminants can often be minimized. The most significant pathway remaining for contamination to influence the environment is through groundwater moving into the Sound. The most important area of this pathway, and the least understood, is the zone of tidally influenced groundwater.

Understanding the processes at work in this zone is critical to cost-effective remediation and revitalization of our urban waterfronts. The Port of Seattle has been investigating these processes in conjunction with specific redevelopment projects, primarily the nearshore disposal of contaminated dredge materials.

From the early '70s to the mid-'80s, increasing environmental awareness focused regulatory concern on contaminated sediments and confined disposal sites. Though these fill sites had not become an obvious problem, there was concern about leachate quality and long-term mass loss.

In 1982, at Terminal 105, the Port constructed a nearshore, upland pit for contaminated dredged material disposal. This was the first Port site monitored for loss of priority pollutants in leachate through groundwater to the nearby estuarine waterway.

This early program found some increased concentrations in the surrounding groundwater during the initial de-watering phase, but nothing that was of concern to the estuary. Arsenic, the only contaminant showing a clear and continuing influence from the dredged material disposal, was of no concern, as it was over 20 times below Marine criteria. This documented success preceded the Port's following three projects, where the majority of this work has taken place.

Terminal 91 Short Fill Modeling and Monitoring

This project was a nearshore fill of contaminated dredged material that was confined behind berms of clean structural sandy gravel, between two existing solid fill piers, and then capped with 16 feet of clean structural material and paved with asphalt. The modeling and monitoring were developed in discussions with the local, state, and federal permitting agencies.

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Southwest Harbor Environmental Impact Statement (EIS)

This EIS for the Redevelopment and Cleanup of Southwest Harbor explored in detail the alternative of creating a multi-source, potentially multi-user, near-shore, dredged material disposal site. The environmental consequences of this alternative were investigated through extensive sampling and modeling.

Terminal 30 (Chevron) Remedial Investigation Feasibility Study (RIFS)

This RIFS, under a Model Toxics Control Act (MTCA) Agreed Order, looks at loss of contamination to the East Waterway from upland petroleum contaminated soils. These soils remain after an old petroleum handling and holding facility (Chevron) was demolished for terminal expansion in the mid-'80s. The redevelopment included the reconstruction of the entire slope facing the East Waterway with a thick layer of clean structural fill, which acts in a similar way to the cleanfill berm at Terminal 91. The active free-product recovery phase of the remediation is now finished, with the recovery of approximately 180,000 gallons of product.

OBJECTIVES

At each site the objective was to find a cost effective, protective way of dealing with contaminated sediments or soils. To provide these solutions, the Port had to increase its understanding of the various processes relating to contaminant movement and attenuation through tidally influenced groundwater on these sites.

At the Terminal 91 Short Fill, the objectives were to predict and monitor the loss of contaminants from the dredged material disposal site. This was important, both over the short term, for impacts on water quality, and over the long term, to assess the total effectiveness of the contained disposal facility. This objective included monitoring the movement of contaminants through the disposal site and attenuation within the berm, assessing the ability of the site to meet the guidelines, and designing remedial actions for potential problems.

In the Southwest Harbor Environmental Impact Statement, the objective was to predict contaminant movement, attenuation, and loss for a proposed multi-source, dredged material disposal site. Here, because of the multitude of potential donor sites for the dredged material and the need to accommodate the most contaminated dredged material possible, it was necessary to provide a range of contaminant levels that would be adequately contained by the design.

In the Terminal 30 (Chevron) RIFS, the objective is to determine the long-term feasibility of attenuating petroleum hydrocarbons across this tidally influenced zone only by these naturally driven processes. Also, it was necessary to understand the processes controlling movement of any free product on the site versus those processes controlling the movement of the groundwater and dissolved contaminants.

METHODOLOGY

The methodology generally involved modeling and on-site measurements of contaminants as well as geochemical and nutrient cycle parameters.

At Terminal 91, we modeled the proposed short-fill using a two-dimensional hydraulic model and a one-dimensional chemical transport model. The modeling demonstrated the feasibility of the project and provided an understanding of the driving forces. With this information, we designed the monitoring plan. We monitored the site during and after construction. This monitoring included detailed chemical analysis of multiple wells, hourly sampling over the full tidal cycle, and additional analysis looking for components that could serve as tracers from the fill through the berm. We reran the model with input from the monitoring to verify and update the predictions.

In the Southwest Harbor EIS, we did a more detailed, two-dimensional slice modeling of the potential nearshore dredge material disposal site. Building on our knowledge gained at Terminal 91, we used a coupled, finite-difference based, fluid flow and transport model (PORFLOW), which allowed us to include: tidal dynamics; buoyancy due to the density differences of fresh and salt water; geotechnical, environment-

specific, adsorption; biodegradation; and salinity dependent "colloidal release" from long-term leaching via upland groundwater. Obtaining the parameters for this modeling effort included extensive sampling of the existing groundwater system as well as doing leach tests with that groundwater on donor-site sediments.

At Terminal 30, we did tidal surveys of the site to define the fluctuating hydrology, we monitored wells within and around the site margins, and we sampled in the waterway for inorganic indicators of the geochemical and nutrient cycles, as well as the contaminants of concern. We also investigated the potential for any small amounts of free product remaining to migrate gradually to the waterway and be released.

RESULTS

The tidally influenced groundwater is a very dynamic transition zone, where the groundwater changes from anaerobic to aerobic, with many resulting geochemical and biochemical changes. The bacterial degradation and geochemical precipitation and adsorption that accompany the transition are the same processes that are active in accepted, engineered remediation technology. Oxygen is added to both the groundwater and the vadose zone. Outflow of upland groundwater is focused in the lower intertidal zone on the last part of the outgoing tides. Also, the mobility of the water through the soil spaces and the incoming high-tide crests serve to keep more viscous petroleum products from moving toward the surface water.

The site-specific results are a chronology of increasing understanding and discovery as the processes were studied in more depth and applied to additional sites.

Terminal 91 Results

The modeling studies, updated by the post-construction monitoring, showed that less than 1 percent of the total amount of any contaminant would be leached in 100 years.

The flow modeling showed that the shallow upland hydraulic gradient, combined with the low permeabilities of the dredged material, was an effective regulator of the movement of contaminants into the high-activity and high-permeability zone of the berm. The high permeability of the berm is essential, as it allows the fresh, oxygenated sea water to penetrate deep within the system and allow these processes to occur over a large area within the berm.

The monitoring data showed that the regulatory requirements and the performance criteria were being met. Levels of a few metals (such as nickel) were elevated in the berm wells, but these metals came from the clean-structural, sandy gravel fill over the dredged material and in the berm.

The majority of the tidal flux is in the intertidal zone in the berm, and the maximum outflow of groundwater is at the end of the lower low ebbing tide. This was observed by doing detailed hourly sampling and detailed chemical analysis for conservative tracers to follow movement of groundwater from the fill through the berm into the slip.

Following concentration of dissolved organic carbon (DOC) across the berm over a full tidal cycle shows this focused outflow of groundwater (Figure 1). The inner berm-face well is completed in the contaminated fill on the inside edge of the structural berm. The berm sample is from the middle of the berm. The outer berm-face sample was taken from within the riprap at the berm face. This shows the concentrations of DOC increasing as the tide falls in the berm with a small spike at the berm face at the bottom of the minus tide. As might be expected, the concentrations drop back down with the influx of fresh sea water. Within the berm and the fill there is a delay associated with the retardation of the tide in the groundwater.

The berm acts as an active biogeochemical filter, trapping trace metals and biodegrading organic contaminants.

Following the relative concentrations of geochemical and nutrient cycle parameters across the fill and berm illustrates the effect of the biogeochemical processes (Figure 2). Oxygen, nitrate + nitrite, and sulfate come into the berm with the sea water through tidal action. Iron (II) and ammonia come in from the contaminated fill. As oxygen enters the outer berm, it is being consumed in the aerobic reduction of organic carbon. As it moves farther into the berm, some is used in nitrification, producing the peak of

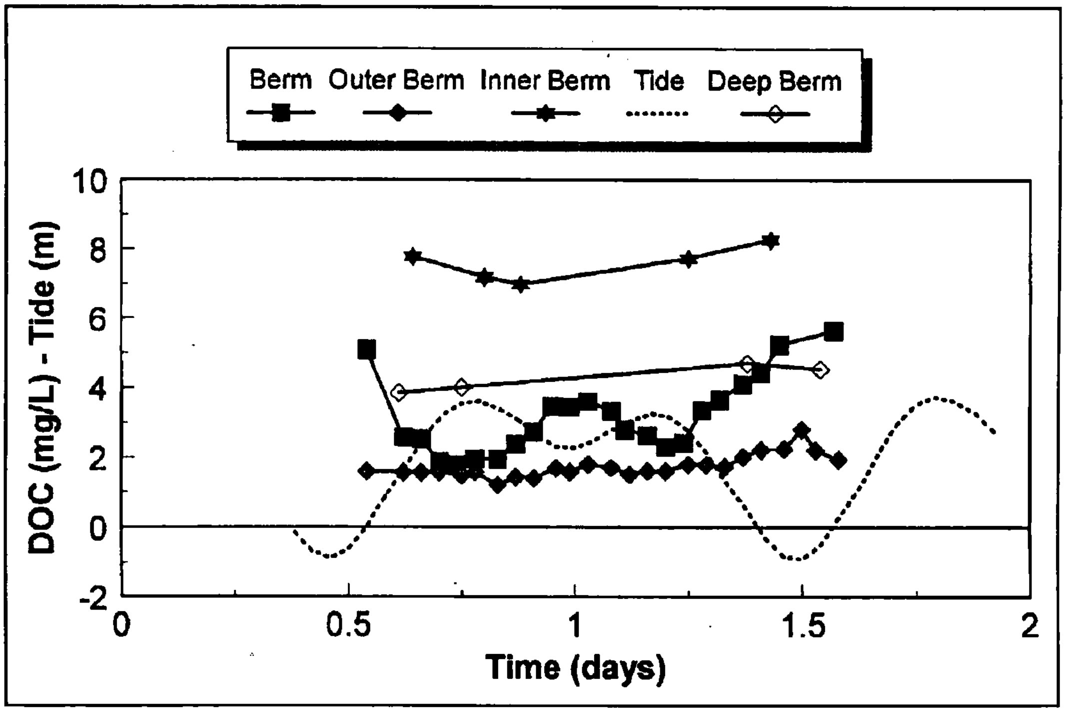

Figure 1. DOC over tidal cycle, Terminal 91

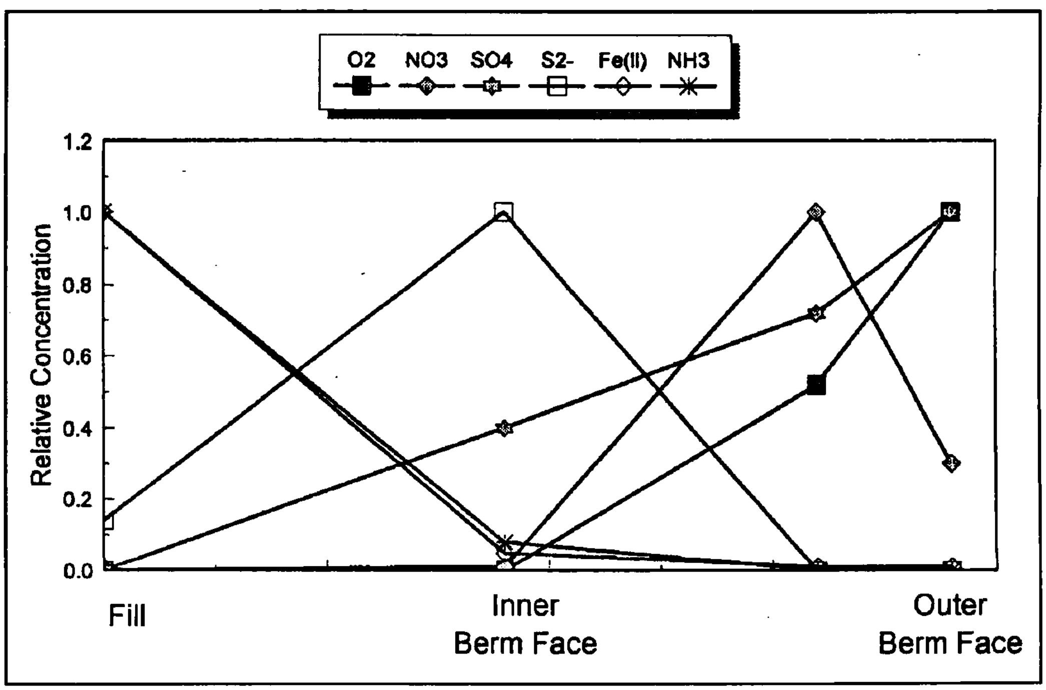

Figure 2. Inorganic biogeochemistry, Terminal 91

nitrate + nitrite in the middle of the berm. In the inner parts of the berm, oxygen is consumed in iron and sulfide oxidation. Sulfate in incoming sea water is reduced by anaerobic bacteria to sulfite, and then to sulfide within the inner berm. Sulfite peaks in the middle of the berm. Sulfide production centers around the inner berm/contaminated fill interface. A small amount of sulfide also originates from the contaminated fill material. This sulfide peak will precipitate metals as insoluble metal sulfides in this area. Ammonia enters from the contaminated fill material and is nitrified by anaerobic bacteria within the berm. These nitrogen compounds provide the nutrients for the bacterial degradation of the organics within the berm. Iron (II) from the fill is oxidized to iron (III) within the berm. This is one of the most important processes, as the precipitating ferric oxyhydroxides simultaneously copercipitate other metals. These oxyhydroxides coat the surfaces of the sandy gravel in the berm and, once formed, are efficient surface active substrates for capturing additional metals from solution.

Southwest Harbor Results

The density differences between the fresh upland groundwater and the dense seawater focuses the flow into the intertidal zone. This density-focused flow, combined with the fluctuations of the tides, restricts this outflow of groundwater to the later stages of outgoing tides. Minus tides (below 0.0 MLLW) are the most concentrated groundwater release. This occurs only over a few hours during the 25-hour tidal cycle. The flow paths through the fill are influenced by the surrounding hydraulic conductivities, but the model shows that contaminant flux out of the site is much more sensitive to the geochemical processes (inorganic K_ds), biological processes (biological degradation rate), and the leaching and colloidal release of contaminants from the fill (salinity-dependent source term).

At this site, the concentrations at the berm and/or the cap did not pose an environmental or human health problem, and the mass loss was less than 1 percent in 100 years for all contaminants (much less for most). Therefore, this site could safely handle most types of contaminated sediments found in the Elliott Bay-Duwamish area.

Terminal 30 Chevron Results

Monitoring showed the processes in the intertidal groundwater zone were sufficient to degrade the TPH in the groundwater to less than 1 ppm, with no BETX compounds within the outer portions of the rebuilt slope. The samples taken in the riprap at the bottom of a minus tide were not different from the background samples in the waterway.

Concerns about potential for any remaining free product to migrate gradually down the average gradient and be released to the waterway were unfounded. The rate of migration of free product of the type found at Terminal 30 was so much slower than the rate of mitigation of water through the soils that if any free product began to move toward the water on an outgoing tide, it would be pushed back again by the incoming tide. Although the average gradient is out to the waterway, only the dissolved fractions will flow out in that direction; free product will continually be displaced inland and redistributed across the soil grains by the recurring crests of the high tide.

Also, during our study of the petroleum product degradation at T-30, we began to realize that the input of oxygen to the bioreactive system in the active wedge of tidally fluctuating groundwater is a two-phased process. During the incoming tide, freshly oxygenated sea water enters the system and mixes with the groundwater. In doing so, it expels an equal volume of air from the pore spaces of the soil. With the outgoing tide, the volume of water leaving the pore spaces of the soil is replaced by a fresh volume of air entering the soil pore spaces. Thus new oxygen is continually entering the system by one of the two active regimes. This is important for processing contamination such as petroleum product with a high biological oxygen demand.

CONCLUSIONS

The processes at work are the same processes functioning in accepted remediation technology. They are controlled by understandable geohydraulic parameters, biochemical reactions, and geochemical

reactions. These sites can be generally understood by monitoring and modeling and the processes incorporated into the design. Understanding this dynamic contaminant attenuating zone can lead to project and remediation designs that take into account these natural processes and are, therefore, more cost-effective solutions to site remediation. Basic site-specific data needs are detailed geohydraulogy over the tidal cycle, existing groundwater chemistry including inorganics depicting major nutrient and geochemical cycles, and porewater chemistry for any proposed fill materials.

POLICY IMPLICATIONS

Point of compliance decisions, monitoring plans, remediation solutions, and cleanup and reconstruction projects that don't take into account the dynamics of this natural in situ treatment zone are needlessly wasting our limited cleanup and restoration budgets. Cost-effective options for existing contaminated property will help prevent unnecessary spread of industrial sites into previously undeveloped, uncontaminated areas. The limited time to achieve final cleanup compliance in engineered, mechanically active remediation is not an appropriate time frame for this hybrid of the treatment/confinement options. In a mechanical remediation, the inclination to cut costs by minimizing maintenance and/or shutting down systems would increase with the time required to achieve the cleanup goal. In this naturally driven system, the longer time is warranted, as the processes are consistent and don't require intervention by the site owner. Site controls and/or deed restriction may be reasonable measures to ensure the geohydraulogy is not detrimentally altered by a future development, and that the structures limiting contact remain in place.

BENTHIC FLUX OF DISSOLVED METALS IN NEARSHORE ELLIOTT BAY

Charles D. Boatman[1] and Allen H. Devol[2]

INTRODUCTION

This study was conducted as part of an evaluation of in-water cleanup alternatives for contaminated sediments for the Port of Seattle's EIS and RI/FS (Parametrix, 1994) for the redevelopment and cleanup of the southwest harbor area of Elliott Bay. The objective of the study was to compare the mass flux of selected inorganic (copper, lead, and arsenic) and organic (naphthalene, fluoranthene, and indeno(1,2,3-cd)pyrene) contaminants in the existing nearshore sediments with the mass flux predicted to be released from two conceptual designs for a confined sediment disposal facility constructed over the nearshore sediments. The predicted mass flux was determined using a coupled, finite difference-based numerical fluid flow and transport model (Hotchkiss and Boatman, 1994; Converse et al., 1993). The measured mass flux was determined using a high-resolution (millimeter interval) interfacial pore water sampler and a benthic flux chamber sampling device. This paper will focus on the results for the inorganic contaminants.

METHODS

Study Area

Measurements were made at two stations located offshore from the former Lockheed shipyard Number 2 in southern Elliott Bay. This area is adjacent to the mouth of the West Waterway of the Duwamish River to the east, and to the former Pacific Sound/Resources wood treatment facility to the west (Figure 1). Station BF1 is in approximately 40 feet of water, and BF2 is in approximately 25 feet of water (MLLW). Sediments at and around these sites exceed the Sediment Management Standards Cleanup Screening Levels for LPAHs and HPAHs and Screening Quality Standards for metals.

Benthic Flux Measurements

Benthic fluxes of metals, organics and oxygen were determined using the *in situ* benthic tripod described by Devol (1987). The tripod contains two stainless steel flux chambers (412 cm^2 each), which are attached to the bottom of a moveable tray. Each chamber lid includes a stirring motor and is connected to a hinged arm at the top of the tray. These arms also contain eight spring-actuated 50 mL polyethylene syringe samplers. The syringe samplers are connected to O-ring sealed, stainless-steel Swagelok® fittings, which penetrate the chamber lid, by nylon tubing. Tritiated water (or other tracers) can be injected into the overlying water through one of the lids that is fitted with an injection syringe. All connecting tubing is filled with deionized distilled water before deployment.

The chambers are open at both ends while the tripod is being deployed. After the tripod settles on the bottom, about 30 minutes is allowed before the tray is released and the weighed tray and chambers are pushed into the sediments. Disturbance of the sediment-water interface is minimal since the top and the bottom of the chambers remain open and the rate of penetration is controlled by a hydraulically damped dashpot. After penetration, about 10 minutes later, the hinged lids are released and are slowly lowered over the chambers controlled by a hydraulically damped dashpot and securely sealed. The spring-actuated 50-mL syringes draw simultaneous sequential samples from each of the two enclosed chambers for a total of eight pre-programmed sampling events. In addition, a modified YSI polarographic oxygen sensor fitted into the lid of each chamber measures the oxygen concentration every 10 minutes. All timed events are

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controlled by an electronics package consisting of the stirring motor electronics, a rechargeable battery pack, a multi-event programmable timer and electronic storage memory for the oxygen measurements.

During sampling, bottom water enters the chambers via a permanently open nylon tube located on the side of each chamber and replaces the water removed by the sampling syringe. Tritiated water (or other chemicals) is injected into the chamber to study the flux of water between the overlying water and the sediment and to determine (through material balance calculations) if the chambers are leaking.

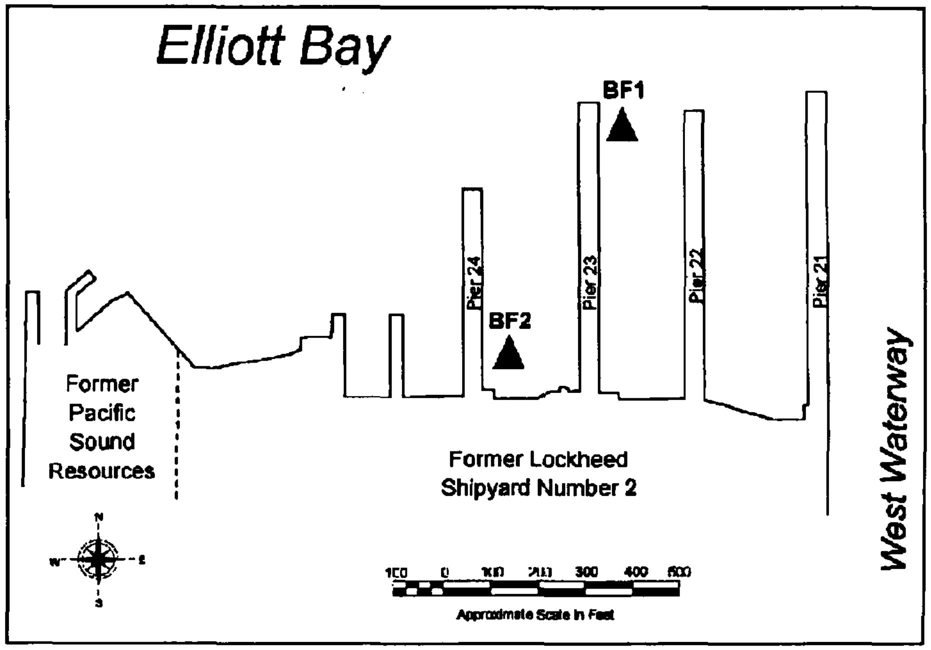

Figure 1. Benthic flux sampling station locations

The benthic tripod was deployed twice at station BF1 and once at station BF2 (Figure 1). The deployments at station BF1 were initiated on November 14, 1991 (BF1-1), November 26, 1991 (BF1-2), and November 19, 1991, at BF2. Each deployment sampled over a period of about 70 hours. The benthic tripod was deployed from the existing piers using a boom truck with a 46-foot boom. Divers assisted in the deployment by releasing the snap hook from the boom cable after the tripod reached the bottom and waiting to check that the chambers were set into the sediments and that the lids were sealed.

The second deployment at station BF1 (BF1-2) was conducted after it was determined that the oxygen was rapidly depleted within the chambers during the first deployments at BF1-1 and BF2. Only a few measurements of contaminant concentrations were collected before the onset of anaerobic conditions in the chambers. Since the purpose of the benthic flux measurements was to establish existing conditions, it was necessary to collect the data under aerobic conditions. Therefore, during the BF1-2 deployment, 50 mL of oxygen gas was injected into the chambers before sampling. Bottom water samples and 2½-inch and 3½-inch surface cores for high-resolution (millimeter depth resolution) interfacial pore water gradient measurements for metals were also collected at each station. Bottom water samples were collected from 10 to 20 centimeters off the bottom next to the tripod at each station using 1.5-liter Niskin bottles.

After retrieval of the tripod, the syringes were removed from the tray, sealed and stored at 4°C for transport to the laboratory for subsampling and compositing. Ten-milliliter aliquots of select syringe samples (approximately 50 mL total volume) were collected for metal analysis. The 10 mL aliquots were directly filtered from the syringe through pre-cleaned 0.4 micron Teflon® filters into pre-cleaned 15 mL polyethylene vials with polyethylene screw caps prior to acidification with 10 µL of ultra-pure nitric acid per milliliter sample via a calibrated adjustable micropipette. All sampling containers, syringes, and filters were acid-cleaned using ultra-pure acid solutions and rinsed with distilled and deionized water in the clean room facilities at Columbia Analytical Services in Kelso, Wash. The cleaned sampling equipment was stored in sealed plastic bags and containers until used.

Following metals sample preparation, samples for organic analyses were composited whenever possible by combining the remaining sample volumes either from a single time step or two sequential time steps from each chamber (i.e., ideally either 80 or 160 mL) into 8-ounce (240 mL) glass containers with Teflon®-

lined screw lids. It was necessary to composite the organic samples because the analyses require at least 50 mL of sample and preferably more than 100 mL.

Benthic fluxes were calculated from the initial change in concentration observed in the benthic flux chamber. This was done for two reasons: 1) aerobic conditions were maintained only for the first few samples during the initial 10 to 40 hours, and 2) the enclosed chamber results in a non-steady state environment with concentrations increasing or decreasing over time and diverging from their initial undisturbed values which will eventually increase or decrease the concentration gradients and therefore the fluxes. All measured concentrations were corrected to account for the change in mass resulting from the partial displacement of chamber water with bottom water as a result of sample collection.

Interfacial Pore Water Measurements

High-resolution (millimeter depth resolution) interfacial pore water gradient samples for metals analysis were collected from the 2½-inch diver cores as part of the benthic flux chamber measurements. These samples were collected using a whole-core surface squeezer (Bender et al., 1987). Due to minimal sample volumes collected, usually less than 10 mL, only metals analyses were possible by employing the highly sensitive multi-element Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS) instrumentation. This data was collected to serve either as a backup and/or as an adjunct to the benthic flux measurements. As a backup, the interfacial pore water gradient measurements would be used to calculate the diffusional flux of contaminants through the sediment/water interface. Backup was necessary since, except for iron and manganese, the benthic flux of metals had not been measured in Puget Sound, and it was uncertain whether the benthic flux chambers would be able to measure the flux of trace metals if the concentration gradients were small. If, on the other hand, the benthic fluxes of trace metals could be measured, the interfacial pore water gradient information would assist in determining the diffusional component of the total benthic flux.

In addition to the whole-core surface squeeze samples, surface sediments from the 3½-inch diver cores were sectioned and centrifuged to extract the surface pore waters. This centrifuge data is used to validate the data obtained using the whole-core surface squeezer. The reason for this validation check is that it has been observed in radioisotope tracer experiments (Bender et al., 1987) that under certain conditions where the pore water concentration gradients of particle-reactive metals are expected to be steep near the sediment-water interface, measured gradients appear to be significantly flattened by the whole-core surface squeeze method. This artifact was thought to be caused by rapid solid-solution re-equilibration as the expressed pore waters come in contact with overlying sediments that have been equilibrated with pore waters with a significantly different metal concentrations.

The whole-core surface squeezer requires collection of undisturbed 2½-inch surface cores with as flat a horizontal interface as possible along with their overlying water. Additional 3½-inch cores were collected for sectioning and centrifuging to collect the pore water from the upper 0-0.5 cm of the sediment surface. Divers were used to collect the cores so that relatively undisturbed core samples could be obtained. Core samples were collected adjacent to the benthic flux tripod stations with typically two of each core type were collected at the same time. Divers then carefully placed plastic core caps over the ends of the cores while on the bottom so that the overlying water completely filled the core. This is an important point for whole-core samples since it insures that with careful handling, the sample will remain undisturbed. The cores were then carefully transported to the laboratory within one hour of sampling.

Each sample was expressed directly into an acid-cleaned, 20 mL polyethylene syringe fitted with a low dead-volume acid-cleaned 0.4 μm Teflon® filter assembly. The sample was then filtered into an acid pre-cleaned 15 mL polyethylene vial with a polyethylene screw cap prior to acidification with nitric acid. The filtered samples were acidified using ultra-pure nitric acid with the addition of 10 μL of acid per mL of sample via a calibrated adjustable micropipette.

The top 0.5 cm of surface sediment sample was extruded from the 3½-inch PVC core barrel into a graduated 3½-inch PVC ring using a wooden piston inserted in the bottom of the core barrel. A thin Lexan plastic sheet was inserted between the top of the core barrel and the PVC ring, and the sediment

sample was placed into an acid-pre-cleaned 50-mL centrifuge tube, sealed, and centrifuged under refrigeration at 9 degrees C for approximately 45 minutes at 10,000 rpm.

The centrifuged sample supernate was transferred directly into an acid-cleaned, 20 mL polyethylene syringe fitted with a low dead-volume acid-cleaned 0.4 µm Teflon® filter assembly. The sample was then filtered into an acid-cleaned 15 mL polyethylene sample container with a polyethylene screw cap. The filtered samples were acidified with ultra-pure nitric acid using 10 µL of acid per mL of sample.

The diffusive flux of metals across the sediment-water interface was calculated only from cores that showed a consistent linear trend of metal concentrations from at least 3 samples collected within the upper few millimeters of sediment. The slope of the linear trend was then determined by linear regression to obtain dC/dz, and the fluxes calculated using Fick's first law of diffusion:

$$Diffusive\ Flux_o = D_{s_o} * \Phi_o * \left(\frac{dC}{dZ}\right)_{Z=0} \quad (1)$$

where D_{so} is the bulk diffusion coefficient at the sediment/water interface (cm^2/sec), and Φ_o is the total porosity at the sediment/water interface (z = 0) (see Converse et al., 1993). A value of 0.862 from Andrews and Bennett (1981) was used to represent the porosity of the upper few millimeters of sediment at the site. This value is for a sandy sediment similar to the sediments at the site.

RESULTS

Average measured total flux of selected metals from the benthic flux tripod and diffusive flux calculations are shown in Table 1.

Table 1. Diffusive and Total Benthic Flux Measurements

Flux (mg/m^2/yr)	Mn	Ba	Metal Cd	Ni	Cu	Pb
Diffusive	600±400	9.8±0.5	0.48	5.3±0.8	16	-3.0±2.5
Total	3,700±600	140±80	0.48±11	130±50	160	-94±80

These fluxes represent only those benthic tripod or pore water data that showed unambiguous results defined by consistent significant trends in concentration over time or depth. An example of the data collected from the three benthic flux tripod deployments is shown in Figure 2 for lead and oxygen within the chamber over time. Figure 2 shows a consistent trend of decreasing initial lead concentrations under aerobic conditions. This indicates that lead is fluxing into the sediments.

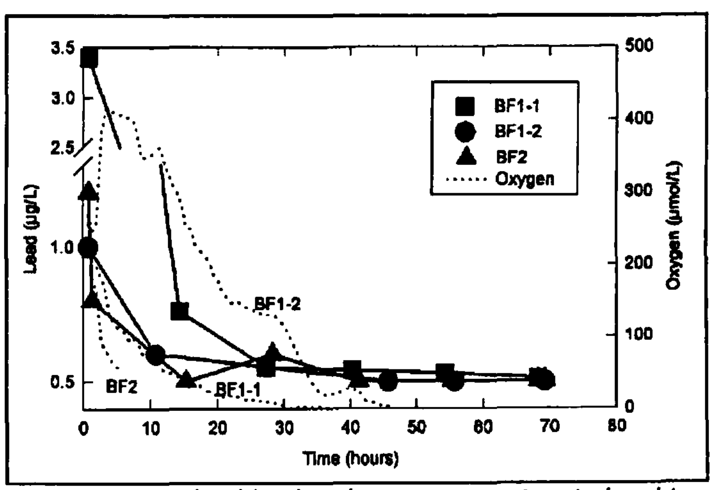

Figure 2. Dissolved lead and oxygen over time in benthic flux chambers

Figure 3 shows an example of the interfacial dissolved lead pore water data collected from the whole-core squeezer cores and the centrifuged core at station BF1. There is a consistent concentration gradient of lead in the

pore water at the sediment-water interface indicating a diffusive flux of lead into the sediments at station BF1. Figure 3 also shows that the centrifuged pore water concentration is consistent with the interfacial squeeze-core data and that the squeeze-core gradients do not appear to be flattened, suggesting that sampling artifacts was not a problem with the lead measurements. Similar confirmations were obtained with the other dissolved metals.

The dissolved lead data are an example of the type of data representing unambiguous results used to determine the total and diffusive fluxes in Table 1. The results in Table 1 suggest that the diffusive flux is only about 5 percent to 20 percent of the total flux into or out of the sediments. The remainder of the flux is most likely due to bioirrigation of the sediments via active burrowing and venting by the benthic infauna. Bioirrigation has been shown to be the major factor in enhancing benthic exchange of oxygen, nutrients, and manganese in other studies (e.g., Devol and Christensen, 1993; Emerson et al., 1984; Aller, 1978).

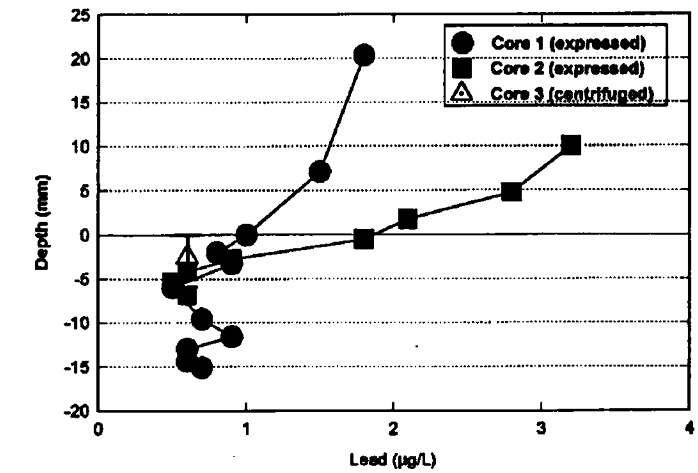

Figure 3. Dissolved lead from whole-core squeezer at station BF1

Comparison of Measured Flux and Model Predicted Flux

The predicted total flux of copper, lead, and arsenic from a numerical model of two confined disposal alternatives (Converse et al., 1993) along with the measured total flux from the benthic flux tripod are listed in Table 2. The two alternatives consist of a large fill, which would contain approximately 600,000 cubic yards of contaminated sediment—referred to here as the "full buildout alternative"—and a smaller fill, which would contain about 85,000 cubic yards—referred to as the "nearshore cap" (Parametrix, 1994). The predicted flux of copper from the nearshore confined disposal alternatives is about 1.5 to 3 times lower than the existing flux, while the predicted flux of lead is about 2 to 6 times lower and of opposite sign from the existing flux. There were no detectable arsenic concentrations from the benthic flux tripod due to the limited sample volume.

Table 2. Comparison of measured flux from the existing sediments with predicted flux from the confined disposal alternatives

Flux		Metal	
($mg/m^2/yr$)	Pb	Cu	As
Full Buildout Alternative	47	118	354
Nearshore Cap Alternative	16	56	540
Existing Sediments	-94	160	No Data

DISCUSSION

The most consistent benthic flux results for both diffusive and total flux of dissolved metals were from manganese, barium, and lead. Of these three metals, it could be argued that lead yielded the most

interesting and significant results, with an average total dissolved flux of about 94 mg/m^2/yr from the overlying water into the sediments.

In order to put the dissolved lead flux into perspective with existing estimates of sources and sinks for dissolved lead in Puget Sound, this sink was compared to the sources and sinks estimated for the main basin of Puget Sound by Paulson et al. (1988). Their estimate in metric tons per year (mt/yr) includes sources from rivers (0.3), municipal and industrial point sources (21), benthic flux (0.1), atmospheric deposition and dissolution (13.3), and advection into the main basin over the sills at Admiralty Inlet to the north and Tacoma Narrows to the south (6). Their only estimated sink was due to advection over the sills (12).

Figure 4 compares the previous source and sink estimates from Paulson et al. along with the revised sink estimate, which includes the benthic flux of dissolved lead into the sediments from this study. The same area of sediments as was used by Paulson et al. (336 km^2) for the main basin was used to calculate the yearly dissolved lead benthic flux sink in metric tons.

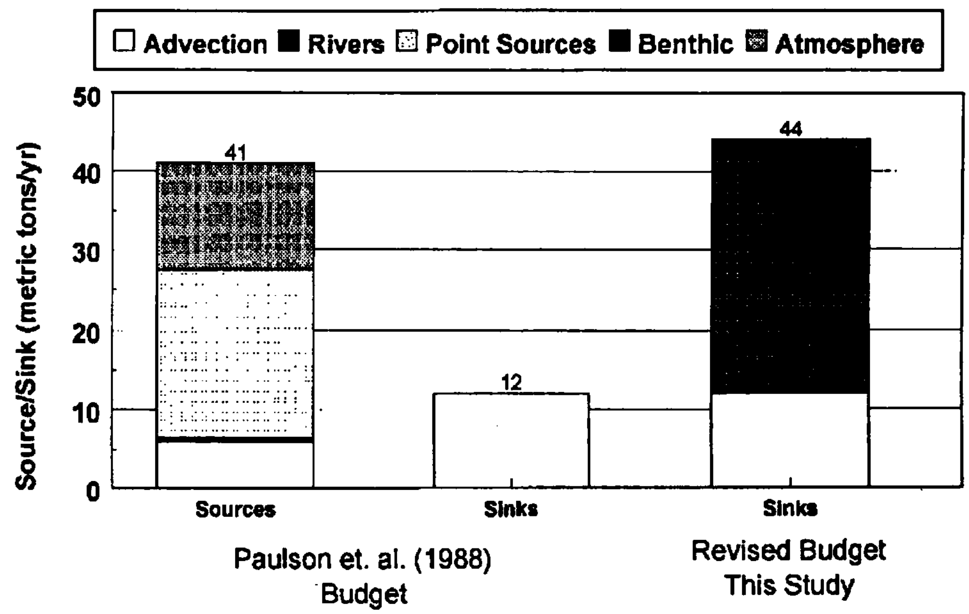

Figure 4. Dissolved lead budget for the main basin of Puget Sound

Figure 4 shows that the excess sources over sinks for dissolved lead from the estimates of Paulson et al. can be put into balance with the estimated sink of 32 mt/yr due to benthic flux. Paulson et al.'s estimate of a 0.1 mt/yr source of dissolved lead from benthic flux was based on a calculation of diffusive flux and not total flux. Their concentration gradient estimate was based on pore water data from centrifuged sections of the upper 0.5 cm of sediment obtained from four box cores from Puget Sound (0.3 µg/L average), and from water samples collected from within the water column (location unknown), which were lower in concentration suggesting a positive flux from the sediments.

However, our measurements showed that bottom water very near the sediment-water interface had higher dissolved lead concentrations than in the overlying water. Measurements in the water column over the site were less than 0.5 µg/L, while bottom water samples collected within 10 to 20 cm from the sediment surface from the flux chambers and with the Niskin samplers ranged from 1 to 3.5 µg/L (Parametrix, 1994). Paulson et al.'s relatively insignificant positive estimate of the benthic flux of dissolved lead is therefore due to the fact that they used the diffusional flux rather the total flux and did measure water samples very near sediment surface.

CONCLUSIONS

We have demonstrated that there were no apparent sampling artifacts from the whole-core squeezer for our dissolved metal measurements.

We have found that the diffusive flux is only about 5 percent to 20 percent of the total flux into or out of the sediments, and that the remainder of the flux is probably due to bioirrigation of the sediments via active burrowing and venting by the benthic infauna.

We found that the predicted flux of copper from the nearshore confined disposal alternatives is about 1.5 to 3 times lower than the existing flux, while the predicted flux of lead is about 2 to 6 times lower and of opposite sign from the existing flux.

We have shown that the excess sources over sinks for dissolved lead in the main basin of Puget Sound found previously (Paulson et al., 1988) can be put into balance with the estimated sink of 32 mt/yr due to benthic flux.

ACKNOWLEDGMENTS

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REGIONAL SOURCES OF MERCURY TO ELLIOTT BAY SEDIMENTS

Clayton Patmont[1]

ABSTRACT

Sediments along much of the southern and central Seattle waterfront contain mercury concentrations that typically range from 1 to 2 milligrams per kilogram (mg/kg), exceeding the chemical criterion of 0.41 mg/kg set forth in the current state Sediment Management Standards. The combined water and sediment quality data available for the Green/Duwamish River and Elliott Bay indicate that a significant source of mercury observed in these sediments is inputs from the upstream headwater reach of the Green River, where substantial deposits of minable mercury are known to exist.

Routine river water-quality monitoring programs conducted by state and local agencies have detected releases of mercury to the river downstream of the identified natural mercury deposits. The 20-year annual loading of mercury through the Green/Duwamish system was not significantly different (within 30 percent) among all reaches monitored (i.e., headwaters; mid-valley; head of the navigable waterway; and mouth at Elliott Bay), suggesting that upstream sources predominate. However, the seasonal pattern and sediment component of mercury transport through the river system vary markedly through the basin. The highest concentrations of mercury occur in the turbulent headwater reaches of the river closest to the mercury deposits, where concentrations peak during seasonal low flow periods. These water column releases subsequently precipitate and settle onto predominantly sandy channel bottoms in less turbulent downstream reaches of the river. In these downstream reaches, mercury concentrations are highest during seasonal peak flow events, concurrent with relatively infrequent periods of significant channel sediment scour.

Based on the available water quality data, the flow-weighted average sediment concentration of mercury that entered the Duwamish Waterway from the Green River over the period 1970 to 1990 was approximately 2 to 4 mg/kg. Most of these sediments settled near the head of navigation of the Duwamish Waterway. As a part of maintenance dredging operations, sediments have been removed (typically biannually) from the waterway and deposited in a deep, open-water disposal site near Four Mile Rock in Elliott Bay. Over the period 1970 to 1990, the mercury concentration in sediments dredged from the waterway averaged approximately 2 to 4 mg/kg, equivalent to the Green River input concentration. Similar concentrations were observed at the Four Mile Rock disposal site. Recent sampling data, however, suggest that both the input and depositional sediment mercury concentrations in the Green-Duwamish basin are declining.

The areal distribution of mercury concentrations in surface sediments in southern and central Elliott Bay, particularly those observed along the Seattle waterfront, is consistent with a regional source of mercury from the Green/Duwamish basin. The vertical distribution of sediment mercury concentrations within this area further suggests that the amount of mercury circulating within Elliott Bay has been declining in recent years. The historical nature of mercury releases to Elliott Bay will be discussed, based in part on the results of recent coring data.

The possible environmental significance of mercury concentrations detected throughout the Seattle waterfront will also be discussed in light of recent environmental and human health studies of mercury-contaminated sediments performed in other similar environments. These recent risk assessment data, particularly those available from Eagle Harbor, suggest that potential hazards posed by sediment mercury concentrations below 2 mg/kg are minor.

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PUGET SOUND RESEARCH '95

SESSION 3A

HABITAT SITES: FUNCTIONS WITHIN AN ECOSYSTEM

Session Chair:

Ginny Broadhurst

Puget Sound Water Quality Authority

EXTRAPOLATION: WHAT IS IT AND HOW CAN IT BE USED TO MAKE SITE-SPECIFIC RESEARCH MORE RELEVANT?

Dixon Landers[1]

ABSTRACT

When conducting long- or short-term environmental research it is imperative that we attempt to answer the question, "To what other sites or areas may I extrapolate my results?" With increasing emphasis directed toward "place-based" research, it makes eminent sense to design these site-specific research studies so that extrapolation is an integral component, leading to achieving the greatest economy and relevance for society's research investment. Connecting site-specific studies directly to a random, probability-based sampling framework, such as that developed by the U.S. EPA's Environmental Monitoring and Assessment Program (EMAP), is one possible way to extrapolate results. It is likely that by using this approach we will be able to directly relate the characteristics of a specific site to the characteristics of a defined subpopulation of similar loci determined by sampling randomly selected sites.

Another approach is to extrapolate site-specific information to an ecological region based on the assumption that defined ecoregions or sub-ecoregions represent generally homogeneous spatial units. In some cases, this "ecoregionalization" approach has been demonstrated to be very robust for certain measurable parameters and appropriate for proposing criteria and goals based on the spatial units. However, ecoregionalization, as a means of extrapolating site-specific studies, is not appropriate for all types of extrapolation, nor was it intended to be. For example, extrapolating aquatic vertebrate distributions or ranges may be limited because of physical barriers that affect distribution and migration. In these cases, a combined approach on watersheds—which define the physical limitations for permanently aquatic species—and ecoregions may be most appropriate. Additional quantitative evaluations and demonstrations of these extrapolation techniques are needed.

By linking a probability-based sampling approach with sub-ecoregionalization, we plan to evaluate various ecological indicators within and among spatial units at the watershed/ecoregion scale to determine the spatial variability and overall suitability of these approaches in case study areas in the Pacific Northwest. This approach will be useful not only for assessing status quantitatively but also for establishing ecological goals or reference conditions and determining change in ecological status (i.e., monitoring design).

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A WATERSHED-BASED WETLAND RESTORATION INITIATIVE FOR WASHINGTON'S PUGET SOUND BASIN

Richard Gersib[1]

INTRODUCTION

The Puget Sound region of northwest Washington state represents a unique and unparalleled ecological resource (Washington Legislature, 1985). In 1985, the Washington legislature created the Puget Sound Water Quality Authority (Authority) to develop a comprehensive plan for water quality protection in Puget Sound. The Puget Sound Water Quality Management Plan was completed in 1987 and revised in 1989, 1991, and 1994. The goal of the plan is to restore and protect the biological health and diversity of Puget Sound. In the 1991 update, a new strategy was added, which called for the restoration of Puget Sound wetlands to assist in meeting the overall goal (Puget Sound Water Quality Authority, 1990). This strategy called on the Washington Department of Ecology (Ecology) and other state and federal resource agencies to develop and implement a wetland restoration program for the Puget Sound basin.

The purpose of the program is to guide and direct non-regulatory wetland restoration within Puget Sound watersheds. The purpose of this paper is to describe the framework developed and timelines established to achieve the program purpose.

METHODS

Technical Work Team

In May 1993 an interagency technical work team was formed, composed of wetland ecologists, and fish and wildlife biologists representing Ecology, U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers, Washington Department of Fish and Wildlife, the Northwest Indian Fisheries Commission, and the Authority. This technical work team developed a draft framework and technical methods for a watershed-based non-regulatory wetland restoration program. Agency representatives were selected for their expertise in wetland ecology, wetland restoration, or wetland functions.

Stakeholder Advisory Group

In March 1994, an informal advisory group of Puget Sound stakeholders was assembled to shape and direct Technical Work Team products into a draft plan. Involved stakeholders included local jurisdictions; tribes; agriculture; timber, conservation and community groups; and state and federal agencies. A facilitated small-group format was used to gain initial participant comments. These comments formed the foundation for a draft narrative plan, which was distributed to advisory group participants for review and comment. Revisions to the draft narrative were made based on comments received and a first draft plan developed for formal review by more than 150 Puget Sound stakeholders. A working draft wetland restoration plan was developed from comments received. The working draft plan represents the combined efforts of many public and private partners and will remain in draft form until all methods have been tested and evaluated in a test river basin.

RESULTS

The plan establishes a fundamental program premise that non-regulatory wetland restoration must contribute to solving watershed problems to be successful. To do this, ecological problems and community needs (i.e., flood control, improved water quality) will be identified within watersheds, characterization and assessment methods will be used to identify where wetlands can be restored to help solve problems and

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meet needs, and work will begin with landowners to restore targeted wetland systems. The following plan framework and timelines establish the structure for program implementation within a river basin.

Fundamental Guiding Principles

Guiding principles agreed upon by the technical work team and advisory group serve as the philosophical building blocks that mold and shape the Puget Sound program. Fundamental principles establish guidelines for developing program goals and serve as the measuring stick for program accountability. Principles have been developed that establish a problem-solving premise and define a scale of analysis, level of public participation, an approach to restoration, plan flexibility, and general evaluation criteria.

Program Goals

The following draft goals establish the purpose and vision for the Puget Sound Wetland Restoration Program:

- Restore and maintain wetlands of sufficient quantity and quality to assist in meeting the Puget Sound Water Quality Management Plan purpose of restoring and protecting the biological health and diversity of Puget Sound.
- Identify ecological problems within watersheds and, where wetlands restoration can address problems, reestablish lost or degraded natural functions.
- Identify community needs within watersheds and restore natural wetland functions that contribute to meeting human health, safety, and quality of life needs of residents.
- Support state and federal policy objectives of no net loss and a long-term net gain in acreage and function of wetlands.

General Program Framework

Public participation, watershed analysis, and the restoration of degraded wetlands must occur if program goals are to be achieved. The following general steps define a framework for reaching established goals within individual watersheds:

- Develop partnerships with local jurisdictions and river basin residents to direct program activities.
- Identify ecological problems and community needs that wetland restoration can address using public input and existing data.
- Identify key wetland functions that contribute to problem/need resolution.
- Conduct watershed analysis to characterize the watershed, classify wetland systems and assess functions.
- Identify wetland restoration sites within each wetland class.
- Create a "menu" of potential restoration sites with a list of each site's anticipated functional gains.
- Restore wetlands opportunistically during watershed analysis and systematically thereafter.
- Monitor and evaluate sites and program.

The plan identifies objectives, strategies, and tasks that support this general framework.

Program Timelines

The working draft plan was completed in November 1994 (Gersib et al., 1994). The Stillaguamish River Basin was selected to test, evaluate, refine, and develop program methods. Information and guidance on program tools such as funding sources, landowner incentives, technical assistance, and participant roles will also be developed and evaluated in the test watershed. It is anticipated that methods development and testing will take approximately one year. After methods testing and program evaluation are completed in

the test river basin, plan methods will be finalized and work begun on the highest priority Puget Sound river basin identified by the Governor's Watershed Coordinating Council.

CONCLUSIONS

The program framework described above is in direct contrast to the site-by-site approach used in the past to restore Puget Sound wetlands. The following benefits are anticipated from this watershed-based program framework:

- Initiates the building of inter-governmental and citizen teams to help solve watershed problems and meet appropriate community needs through restoration.
- Does the up-front technical and public participation work to ensure areas and problems of greatest concern are addressed first.
- Does the up-front technical work to take advantage of short-term funding opportunities.
- Provides access to a diverse group of earmarked funds by matching wetland restoration sites with targeted functions such as water quality, flood control, and anadromous fish and migratory bird habitat.
- Complements regulatory process by providing technical information on how wetlands contribute to watershed system function to improve mitigation site placement.
- Provides information, assistance, and training to individuals, organizations, local jurisdictions, and tribes interested in restoring wetlands.
- Creates more support for wetland protection and stewardship.
- Restores wetlands.

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ECOLOGICAL FUNCTIONS OF A SALTMARSH/MUDFLAT COMPLEX CREATED USING CLEAN DREDGED MATERIAL AT JETTY ISLAND, WASHINGTON

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INTRODUCTION

The Jetty Island berm project was planned, designed, and coordinated by the Port of Everett (Port) and the U.S. Army Corps of Engineers, Seattle District (COE), to demonstrate beneficial use of clean dredged material for habitat development. By creating a sand berm on an existing island, the Port and the COE expected four objectives to be met within five years: 1) to balance erosion losses on the exposed west side of the island, 2) to create additional American dunegrass (*Elymus mollis*) habitat, 3) to create a protected embayment that would be naturally colonized by marine invertebrates, and 4) to demonstrate a beneficial and economical disposal option for clean dredged material. The protected intertidal mudflat within the embayment was expected to contribute to increased productivity and biomass of fish prey and, therefore, improved habitat for juvenile salmonids outmigrating to northern Puget Sound.

Construction of the federal navigation channel in Everett Harbor from 1894 to 1903 resulted in large volumes of sediment requiring disposal. Creation of Jetty Island began in 1903 with construction of a rock jetty behind which these dredged materials could be placed. COE maintenance dredging of the channel and settling basins (Figure 1) continued to build the island until 1969. Today Jetty Island is approximately 3 km long and covers approximately 40 ha (100 acres) above mean higher high water (MHHW). Upland vegetation is dominated by scot's broom (*Cytisus scoparius*), blackberry (*Rubus* spp.), and many other shrubs and herbaceous species. Extensive mudflats and Saratoga Passage lie to the west of the island; the Snohomish River estuary, the federal navigation channel, and the city of Everett lie to the east (Figure 1).

In the mid-1980s, the COE identified an opportunity to enhance and increase existing Jetty Island habitat with material from maintenance dredging of the channel and lower settling basin. In 1987, an Agency Technical Advisory Committee (ATAC) was formed to develop specific project details. An environmental assessment of the area was completed before placement of dredged material (COE, 1989a). Abundance and distribution of benthic infauna and epibenthic Crustacea were investigated as well as use by resource species (salmon, Dungeness crab, bird). Environmental design and monitoring programs were finalized in the Implementation Plan (COE, 1989b), which stated project objectives, responsibilities of participants, performance standards, and methods for evaluating and monitoring success.

Specific monitoring was required over five years. A quantitative assessment method was developed to evaluate pre- and post-project juvenile salmon habitat losses and gains. For the project to be considered a success, surveys were required to demonstrate that 1) juvenile salmonids use the project area, and 2) juvenile salmonid habitat is increased by at least 10 percent over pre-project levels. Other studies evaluated the physical stability of the berm and the success of experimental plantings of saltmarsh vegetation within the lagoon formed by the berm. Success of saltmarsh habitat development will be achieved at Year 5 if at least 40 percent of the plant community inside the berm between +6 and +10 ft MLLW is not statistically different from that of the saltmarsh reference site located on the eastern side of the island (Figure 1).

Hydraulic maintenance dredging was completed January 6, 1990. A 550-m (1,800-ft) long berm, occupying a little over 5.3 ha (13 acres), was created by placement of 323,000 cy of clean sands and silts on the west side of Jetty Island. Placement of the berm created a 7.7-ha (19-acre) mudflat within a protected embayment on what had been the sandy west shore of the island.

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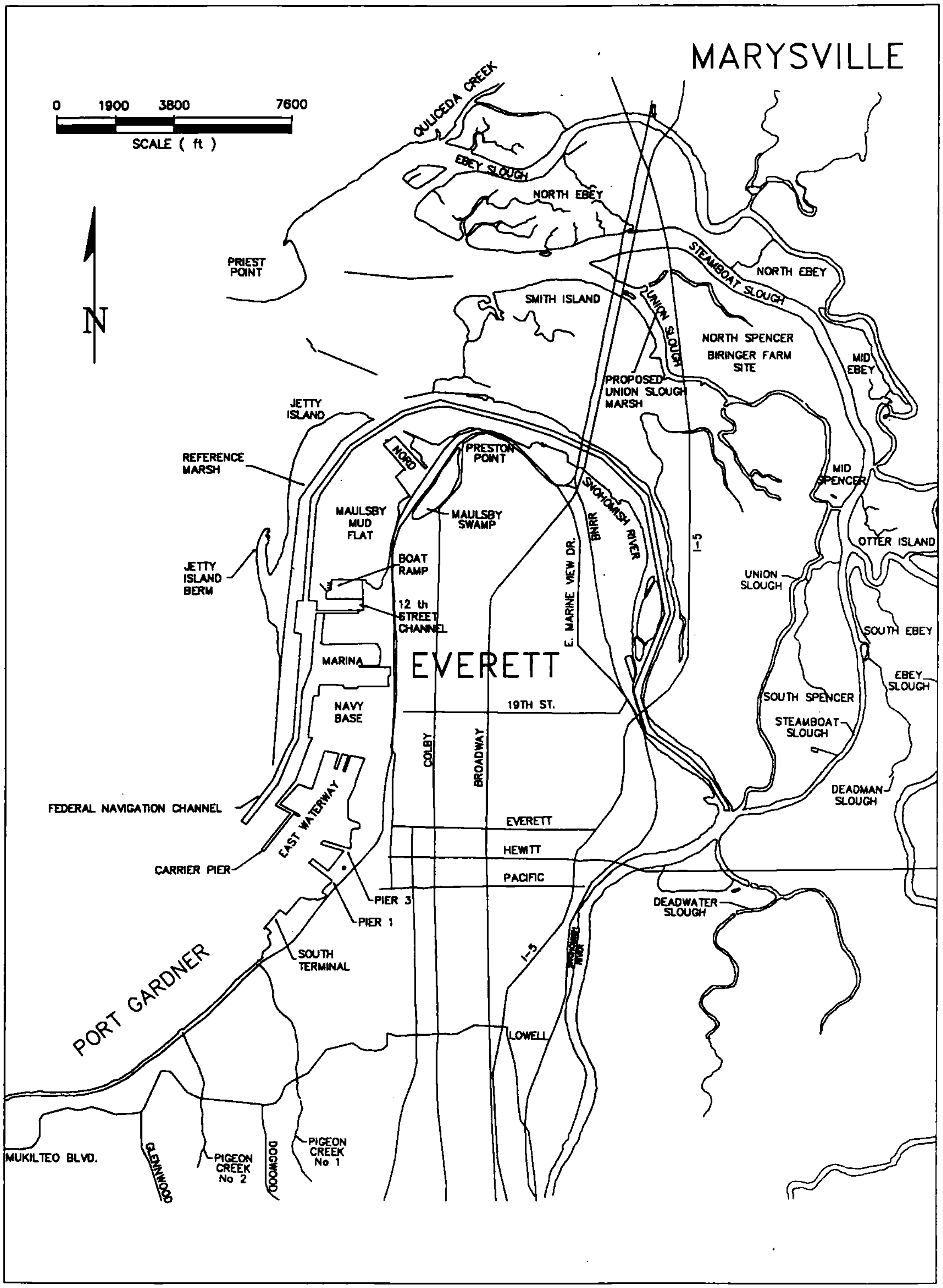

Figure 1. Port Gardner and the lower Snohomish estuary

METHODS

Physical Monitoring

The COE developed physical performance criteria for the project and monitors physical features (i.e., coastal geomorphology, topography). Approximately 65,000 cy of the berm was predicted to erode over 10 years. As long as the berm erosion rate does not exceed this predicted rate by more than 25 percent, the frequency of nourishment required to preserve it should be about every 10 years (COE, 1989b). The COE has completed yearly surveys to assess the stability of the berm and developed a post-project bathymetric map in 1992.

Biological Monitoring

Epibenthic zooplankton was sampled in April and May of 1992 using a 0.018-m^2, battery powered epibenthic sampler. Three replicate samples were analyzed from each of 18 stations representing three depth strata (+9, +6, and +3 ft MLLW) inside and outside the berm. Samples were sieved on a 0.25-mm^2 screen, and zooplankters recognized as key prey taxa for juvenile pink and chum salmon were enumerated and wet weighed.

To evaluate the success of the project in terms of juvenile salmonid habitat, an equation was developed and adopted by the ATAC to describe the quality of the habitats in terms of biomass of key prey species and other relevant factors. This equation (COE, 1989a; Pentec, 1994) is as follows (see Table 2 for definitions of factors):

Habitat Units (HU) = Acres XPWF X (Cover factor + Slope factor) X RIF

Fish use of the area was evaluated using a 40-m (130-ft) beach seine in the spring of 1992 and 1994 under high-tide conditions at locations inside and outside the berm.

Because the artificial establishment of saltmarsh vegetation in urban estuaries of Puget Sound was not well understood, experimental planting was conducted in 1990, immediately after placement of the dredged material, to determine at which elevations within the embayment saltmarsh vegetation would survive. Experimental plugs of *Deschampsia caespitosa, Carex lyngbyei, Triglochin maritima,* and *Scirpus maritimus* were obtained from Wave Beach Grass Nursery in Florence, Ore. Plugs of native saltmarsh vegetation, predominantly *Distichlis spicata*, were dug separately from a reference marsh on the east side of the island (Figure 1). Dunegrass also was planted over approximately 1.5 ha (3.6 acres) along the western side of the berm.

By September 1990, it was apparent that vegetation would survive only within a limited area of the embayment; thus, plantings in the spring of 1991 focused on areas between +9 and +12 ft MLLW. *Distichlis*-dominated plugs collected from the reference marsh were planted along the inside of the berm primarily between +11 and +12 ft MLLW to augment *Distichlis* surviving from the 1990 plantings. *Salicornia* and *Jaumea* plugs from Wave Beach Grass Nursery were planted primarily between +9.5 and +11 ft MLLW along the inside base of the berm (southern tip of the protected lagoon) approximately 106 m to the north along the inside of the berm and approximately 40 m north along the island shoreline (east side of the lagoon).

Field monitoring was conducted in September 1993 (Year 3) to measure the success of the saltmarsh plantings in 1991 as well as natural colonization. In the project planting area, three relatively distinct vegetative zones were noted:

1. A lower zone between +9.5 and +11 ft MLLW that was dominated by *Jaumea carnosa* with a significant component of *Salicornia virginica* (the "lower zone" or "*Jaumea/Salicornia* zone").

2. An upper zone between about +11 and +12 ft MLLW and continuing up into the supralittoral in some areas that was dominated by *Distichlis spicata*, *E. mollis*, and *Spergularia* (the "upper zone" or "*Distichlis/Elymus* zone").

3. A supralittoral zone generally above +12 ft MLLW that was dominated by *E. mollis* from natural colonization.

The *Jaumea/Salicornia* and *Distichlis/Elymus* zones were sampled as distinct strata; the supralittoral zone was not sampled. North of the planted area, the pattern of three distinct zones was not evident, and a single zone dominated by *Spergularia* was sampled between about +9.5 ft and 11.5 ft MLLW. The reference marsh was sampled to gauge success of the marsh developing within the protected embayment. A small sub-embayment inside the first small spit that has formed at the end of the berm was also sampled to document natural colonization that is occurring there. Percent cover was determined by species on 25 0.25-m^2 quadrats randomly placed over the upper and lower zones within the inner berm and at the reference site. Similar data also were recorded for the reference area and the "point" area at the tip of the berm. Individual species cover values were summed to derive total cover in the quadrat.

Randomized analysis of variance (ANOVA) and t-tests (Edgington, 1987) were used to test for significant elevation or site differences in species cover and total plant cover.

RESULTS

Physical

A portion of the western side of the berm began eroding during winter storms in 1990/1991 and has continued to erode. Natural beaching of logs, supplemented by placement of old boomsticks by Port staff, has added some stability to the berm; some originally planted and subsequently colonized dunegrass, however, has been lost to erosion. Two small sand spits have formed at the end of the berm (Figure 2), creating small protected flats at about +9 to +10 ft MLLW. By early 1991, some areas along the eastern side of the embayment became eroded or covered with sand that had been transported by storms. Elevations changed from 0.5 to 2.0 ft within the embayment. Woody debris from the dredging formed thick mats (to 20 cm) over some areas inside the embayment. These mats have gradually dissipated to the point that their coverage is insignificant to epibiota.

Biological

Epibenthic zooplankton productivity

The biomass of epibenthic fauna from Year 2 samples was dominated by Crustacea other than key prey species at all locations (Table 1). In May 1992 densities and biomasses (Table 1) of key prey taxa were generally well below those in April except at +9 ft MLLW in the inner berm and at +3 ft MLLW at all stations. Key prey taxa were present inside the berm at +6 and +9 ft MLLW but not along reference transects at these same elevations. As a result, the biomass of key prey taxa was significantly higher at +9-ft-MLLW inside berm stations in May than at the comparable stations in the reference area (randomization t-test; $p < 0.10$). The biomass of key prey taxa was significantly lower in the project area at the exposed +3-ft-MLLW stations in May than at the comparable reference area stations; as a result, biomass was lower for the combined (both months) exposed stations in the project area than in the reference area ($p < 0.01$).

Salmonid habitat evaluation

Project area PWFs from the Year 2 data were greater than 1.0 at the +9- and +6-ft-MLLW elevations but less than 1.0 at the +3-ft-MLLW elevation (Table 1). The high PWFs at upper elevations in the project area occur because of the greatly enhanced abundance of key prey taxa within the protected embayment. High key prey taxa biomass in May 1992 at the +3-ft-MLLW elevation in the reference area dominated the biomass trends and led to an overall low PWF for the project area at this elevation. The higher reference area key prey taxa biomass was caused by a high abundance of the amphipod *Anisogammarus confervicolus*, one of the most common amphipods in the North Pacific. Habitat units have been calculated

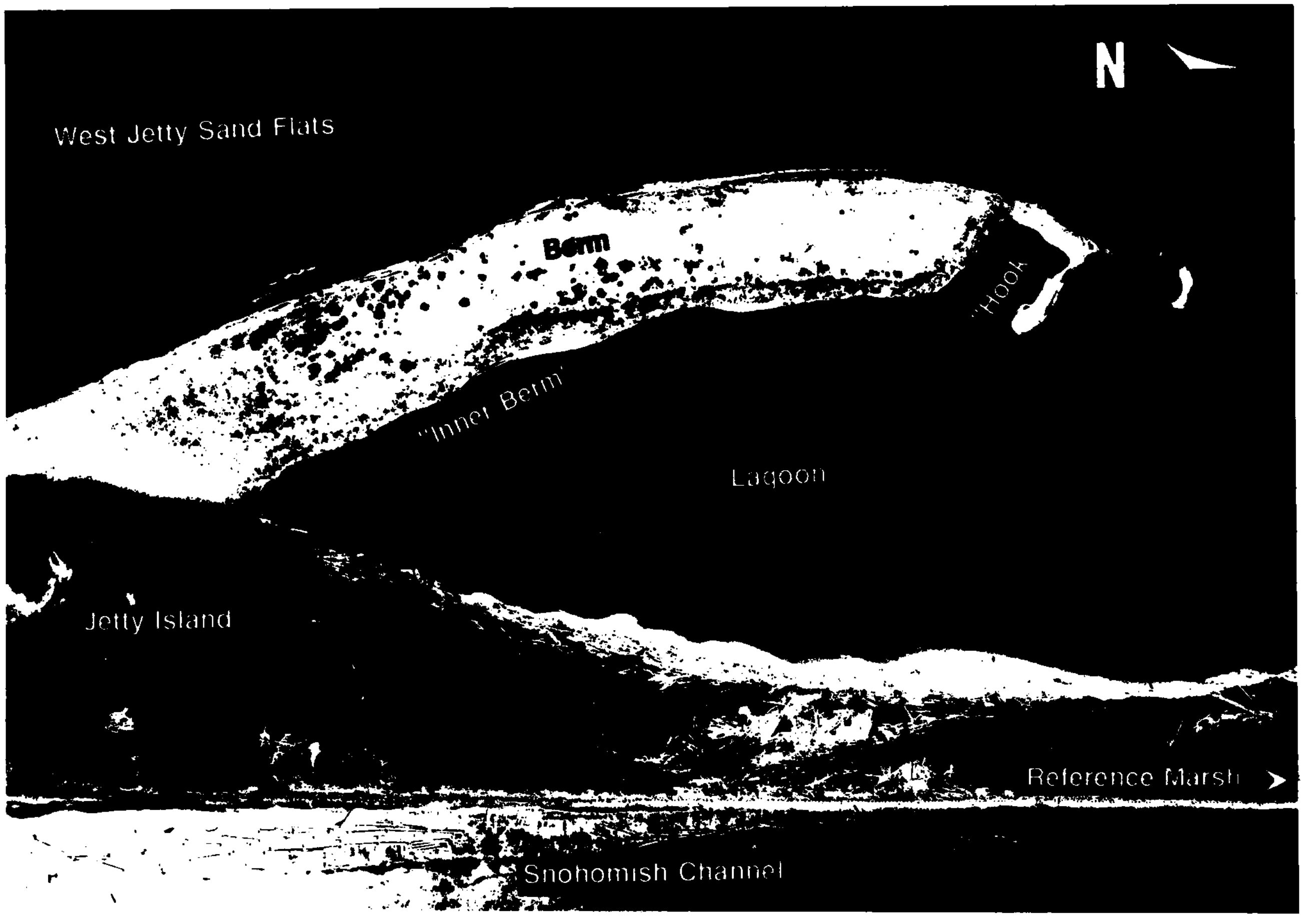

Figure 2.

Table 1. Mean key prey biomass and the prey weighing factor (PWF; April and May data combined) from epibenthic sampling at Jetty Island, 1992

		Biomass (grams/square meter)			Prey weighting factor		
	Elevation	Reference	Project area		Reference	Project Area	
Month	in ft MLLW	area	Inside	Exposed	area (=before)	Inside	Exposed
April	9	0.001	0.176[a]	0.000	1.00	215.00	0.00
	6 or 7	0.002	0.001	0.109	1.00	3.50	54.50
	3	0.002	- -	0.001	1.00	- -	0.01
May	9	0.000	0.040[a]	0.000			
	6 or 7	0.000	0.006	0.000			
	3	0.501	- -	0.004			

[a] Includes four inside berm +9-ft-MLLW stations. The +7-ft-MLLW transect is included in the +6-ft-MLLW category.

using Year 2 PWFs, 1993 percent cover data from project planting area (inner berm), and habitat areas (acreages) derived from the COE May 1993 reconnaissance flight.

The habitat loss of approximately 13.2 acres between +2 ft and +12 ft MLLW (the area of berm above +12 ft; Table 2) eliminated production of prey items for juvenile salmon; to avoid a net loss of salmon feeding opportunities, one success criterion for the project was that the habitat units calculated by the above formula be at least 10 percent above the pre-project level at Year 5 (1995). The high epibenthic zooplankton productivity in the mudflats within the protected embayment generated a high PWF that in turn led to a calculation of a high number of habitat units and a high percentage (more than 4,000 percent) of increase in habitat over pre-project conditions.

There is a high variability in Year 2 epibenthic zooplankton data, which leaves some uncertainty regarding the present analysis; these data nonetheless suggest that the project will meet the salmonid habitat criterion (present habitat units 110 percent of pre-project condition) in 1995.

Fish use of the area

Beach seining in 1992 and 1994 confirmed that juvenile salmon were present within the Jetty Island lagoon and at two reference areas during their outmigration from the Snohomish River system. Mean catch in the project area in 1994 (1.2 salmon/set) was somewhat lower than that from the West Jetty Island reference transects (8.3 salmon/set) and substantially lower than those from the north end of the island (71.0 salmon/set). Mean catch/set of juvenile pink salmon at the exposed sites on the berm was greater than catches in the reference areas, which are also exposed. However, catches of juvenile chum salmon were substantially higher at the reference stations than in the project area, exposed or sheltered. Regardless, the presence of juvenile salmonids at the six project sites sampled indicates use of the project area as required by the criterion for success.

In addition to chum and pink salmon, several other fish species were captured in 1994. Numbers of juvenile surf smelt (*Hypomesus pretiosus*) were much higher in the project area (547 smelt; 49.7/set; averaging 47 mm) than in the reference areas. Catch of staghorn sculpin was also much higher in the project area.

Vegetation

Mean percent cover for each plant species and mean total percent cover for the upper and lower zones in the inner berm were compared with similar zones at the reference site (Table 3). In the upper zone, there was no significant difference in percent cover of *Elymus* or *Distichlis* between the inner berm and the reference site. In the lower zone, no significant difference was found in percent cover of *Jaumea* and *Salicornia* between the two sites. Several other taxa and the total percent cover of all taxa combined differed significantly in both the upper and lower zones. The width of the upper (*Distichlis/Elymus*) zone ranged up to about 3 m. This zone extended a distance of 99 m and encompassed an area of 0.04 acre with a mean cover of 25 percent. The lower (*Jaumea/Salicornia*) zone extended about 171 m and included an area of 0.16 acre with mean cover of 59.1 percent.

DISCUSSION

Physical

Before the berm was created, no mud substrate occurred on the west side of Jetty Island. A total of 76.7 acres of sandy habitat was present between the elevations of +2 ft and +12 ft MLLW. A portion (3 acres) of the present-day project area was below +2 ft MLLW before the berm was constructed. Creation of the berm displaced the post-construction 2-ft contour up to 100 m west of the pre-project 2-ft contour in some places.

When the berm was originally created, it occupied about 15 acres above +12 ft MLLW; as of the 1992 survey, only about 13.2 acres remain above this elevation due to erosion of the berm. Thus, the project has resulted in the loss of 13.2 acres of intertidal sandflat.

*Table 2. Pre- and post-project habitat area (acres) and quality (habitat units)**

	Mud								Sand												Summary					
	Without berm		With berm (1993)						Without berm						With berm (1993)						Total acres			Habitat units		
Elevation (MLLW)	Area	HU	Area	Slope	Cover	PWF	RIF	HU	Area	Slope	Cover	PWF	RIF	HU	Area	Slope	Cover	PWF	RIF	HU	Before	After	Change	Before	After	Change
+12 to +10 ft	0.0	0.0	3.1	0.5	0.0	215	1.0	331.3	3.1	0.5	0.0	1.0	1.0	1.5	2.7	0.5	0.0	0.0	1.0	0.0	3.1	5.7	2.6	19	331	313
+10 to +8 ft	0.0	0.0	6.5	0.5	0.0	215	1.0	722.2	4.9	0.5	0.0	1.0	1.0	2.4	2.4	0.5	0.0	0.0	1.0	0.0	4.9	8.9	4.0	19	722	703
+8 to +5 ft	0.0	0.0	9.6	0.5	0.0	3.5	1.0	16.7	24.1	0.5	0.0	1.0	1.0	12.1	21.0	0.5	0.0	54.5	1.0	572.5	24.1	30.6	6.5	29	589	560
+5 to +2 ft *	0.0	0.0	0.0	0.5	0.0	0.0	1.0	0.0	47.7	0.5	0.0	1.0	1.0	23.8	21.3	0.5	0.0	0.0	1.0	0.1	47.7	21.3	-26.3	41	0	-41
Total +12 to +2 ft	0.0	0.0	19.2					1,070.2	79.7					39.9	47.4					572.6	79.7	66.5		108	1,643	
Area gain (loss)																							-13.2			
Habitat units gain (loss)																										1535
Percent change																							-16.6%			1,423%

* The project area is defined vertically by the 1989 +12-ft-MLLW contour and the 1993 +2-ft-MLLW contour. A portion of the project area that is currently above +2 ft MLLW was below that elevation before the berm was constructed in 1989. The difference of 13.2 acres represents area filled to above +12 ft MLLW to form the berm.

Key

HU (Habitat Units) = Acres x PWF x (Cover factor + Slope factor) x RIF

PWF = Prey Weighting Factor, local mean key prey species biomass/reference area key prey species biomass at same elevation. Data from April and May 1992 sampling (see Table 1).

Cover and slope factors are defined in Pentec 1994.

RIF = Relative Regional Importance Factor, a recognition that some habitats are more valuable because of past losses. Assigned a value of 1.3 for saltmarsh areas.

Assumptions

RIF of 1.3 and cover factor of 0.2 assigned to 0.04 acres between +10 and +12 ft MLLW with average vegetative cover of 25 percent.

RIF of 1.3 and cover factor of 0.4 assigned to 0.16 acres between +8 and +10 ft MLLW with average vegetative cover of 59 percent.

Table 3. Mean percent cover for individual plant species September 3, 1993 (n = 25 for each taxon)

		Reference		Berm				
				Inner			Point	
	Taxon	Mean	SD	Mean	SD	*p*	Mean	SD
Upper Distichlis/Elymus	*Jaumea carnosa*	8.30	16.70	3.20	8.50	0.1318		--
	*Salicornia virginica**	13.10	19.50	0.30	1.00	0.0001	0.70	1.40
	*Spergularia marina**	2.40	3.10	0.10	0.25	0.0003	7.40	14.10
	Distichlis spicata	15.40	9.80	12.60	9.90	0.2450	--	--
	*Atriplex patula**	1.90	2.80	0.10	0.25	0.0005	1.80	9.00
	Elymus mollis	4.60	19.10	7.30	17.50	0.5033	--	--
	Total cover*	46.38	25.80	25.03	20.48	0.0070		
Lower Jaumea/Salicornia	*Jaumea carnosa*	43.30	39.20	34.70	?	0.3103	--	--
	Salicornia virginica	8.30	13.70	9.20	?	0.6863	--	--
	*Spergularia marina**	0.00	0.20	13.20	?	0.0001	--	--
	*Distichlis spicata**	51.70	36.80	1.40	?	0.0001	--	--
	Total cover*	111.00	16.55	59.10	42.50	0.0001		

* $p \leq 0.01$

Biological

As expected, depositional conditions within the 19.2-acre mudflat inside the berm have greatly favored the production of invertebrates including epibenthic prey of juvenile salmonids. Based on the 1992 epibenthic zooplankton abundances and the 1993 bathymetry, it appears highly probable that the project will meet the criterion of providing > 110 percent of pre-project habitat units for juvenile salmonids. Presence of juvenile salmon within the lagoon in 1992 and 1994 has met the criterion for demonstration of salmonid use of the area.

Although no infaunal monitoring was required under the Implementation Plan, qualitative observations confirmed a rapid colonization of the projected embayment formed by the berm. Early in the spring of 1990, there was a substantial colonization of the mudflat below about +8 ft MLLW by ghost shrimp (*Callianassa californiensis*). Since 1990, qualitative excavations within the lagoon have shown a continual increase in the apparent density and diversity of the infaunal community, with polychaetes, crustaceans, and molluscs all contributing to this assemblage. By summer of 1992, small softshell clams (*Mya arenaria*) were established along the firmer muddy sand along the inside of the berm between about +7 and +8 MLLW. Although elevations within the lagoon are relatively high (i.e., > 6 ft MLLW) for Dungeness crab, some use is indicated by an observation of a small (approximately 3 cm) crab molting in the moist mud of the lagoon.

The abundance of shorebirds, smelt, and flatfish as well as the juvenile salmon feeding on benthic and epibenthic prey within the lagoon demonstrate that the project area is functioning as an important part of the Port Gardner ecosystem.

Natural colonization of vegetation on the top of the berm has been remarkable. Seedlings of some 12 to 15 species became established in the spring of 1990, and the vegetative community has continued to develop rapidly with species such as bighead sedge and beach peavine that are also dominants on drier areas of the main island. During an August 1994 survey, we collected more than 40 species of vascular plants on the center of the berm (e.g., above +12 ft MLLW). The berm now supports several shrub and

tree species (e.g., scot's broom and black cottonwood [*Populus balsamifera trichocarpa*]) that have grown to more than 2 m in height.

Dunegrass plantings in 1990 were very successful and continue to expand beyond and between the planted rows along the west side of the top of the berm. A portion of this area planted with dunegrass has eroded away, and it appears that the rhizome mat of the grass is only marginally helpful at retarding this erosion. A similar erosion of the dunegrass community was occurring before berm construction along much of the northwest shore of the island. The dunegrass plantings and natural colonization by other species have significantly retarded wind erosion on the top of the berm, however. Natural colonization of dunegrass from waterborne seeds and rhizomes from eroding areas of the island to the north has developed into a similarly dense growth along the lower elevations (+12 to +14 ft MLLW) on the east side of the berm.

The nearly complete lack of success of the 1990 experimental plantings of saltmarsh plants in the lagoon contrasts sharply with the success of the 1991 plantings and subsequent natural colonization. Quantitative sampling in late summer of 1993 demonstrated considerable success of species planted in 1991 and in some areas of natural colonization. The lack of a statistically significant difference in cover in some of the dominant species between the berm and reference marshes (*Jaumea, Distichlis, Elymus* in the upper zone; *Jaumea, Salicornia* in the lower zone) is highly encouraging. Over much of the planted areas of the lower zone, the combined cover of *Jaumea* and *Salicornia* exceeded 100 percent, and *Jaumea* was in bloom in early September 1993. Differences in other species and in total cover remain, however, and it is unlikely that the vegetative communities in the two areas (berm inside and reference marsh) will ever be identical because of subtle environmental differences, most notably in salinity regime. However, it is expected that the healthy and expanding saltmarsh fringe on the inside of the berm will develop into a significant and beneficial habitat feature that would otherwise be lacking on the west side of Jetty Island. A disturbing finding has been the discovery in 1994 of a large number of plants of the invasive exotic *Spartina ?anglica*; the Port has initiated an eradication program.

Sampling of fish and invertebrate use of the lagoon at high tide demonstrates that several functions (fish use, feeding, and refuge; invertebrate production) of a natural saltmarsh are also provided by this fringe marsh. Qualitative observations also suggest that important marsh functions of use by shorebirds and waterfowl as well as organic detrital production are occurring as well.

Beyond its documented use by immense numbers of juvenile surf smelt and lesser numbers of salmon and other fish, it seems likely that the greatest single ecological benefit of the berm and lagoon has been its suitability for a variety of ecological functions of birds. Virtually all the bird species reported in the baseline studies have been observed to use the berm and/or lagoon, often in greater numbers than seen elsewhere on the island. Construction of the berm added three important bird habitats not previously found on the west side of Jetty Island: unvegetated sandy uplands, saltmarsh, and mudflats. Each of these habitats is used differently by birds, but collectively they constitute a habitat complex similar to some of the better habitats found in more natural estuaries. Although the unvegetated sandy uplands have been reduced in area by vegetative colonization since construction, the two lower spits that have formed on the north end of the berm continue to offer this type of habitat.

SUMMARY

The Jetty Island berm project continues to be monitored for its success at habitat development and beneficial use of dredged material. Evaluation of performance standards to date, Year 4, indicates that the project is meeting the criteria established in the Implementation Plan and suggests that the productivity of the protected embayment will exceed project goals for salmonid habitat evaluation. This joint project between the Port and the COE will be evaluated for overall success at Year 5 (1995). Interim monitoring has shown that the area is being used by juvenile salmonids and has met the criterion for demonstrated use in at least two years. Year 3 monitoring showed that the percent cover of selected plant species in the planted portion of the protected embayment is not statistically different from that in a reference marsh, although other taxa do differ significantly.

The abundance of juvenile salmon prey resources has enhanced the project area habitat value for juvenile salmonid feeding and for use by juvenile surf smelt, an important forage fish. Results of the Year 2 salmonid and epibenthic zooplankton surveys, reevaluated here with known habitat areas, confirm that salmonid habitat has increased over pre-project levels. In fact, this increase is about 4,000 percent (Table 2). As anticipated, the lower energy regime and mud substrate of the protected embayment is providing a more productive habitat for juvenile salmon prey resources than exists on the more exposed sandy beaches outside the berm. This gain in productivity within the embayment has more than offset productivity lost by filling 13.2 acres of previously intertidal habitat to greater than +12 ft MLLW.

FUTURE MONITORING

The following future monitoring efforts are required by the Implementation Plan:

- Vegetation monitoring. In addition to the survey conducted in 1993 and reported here, the Port will repeat a quantitative survey of the saltmarsh vegetation within the inner berm and reference site in 1995 and in 1997.
- Fish surveys. Beach seining by the Port is no longer required. 1992 and 1994 sampling have demonstrated outmigrating juvenile salmonid use of the project area.
- Epibenthic sampling (1995 and 1997). By monitoring epibenthic abundance, an integral component of the salmonid habitat unit, the importance of the new habitat to juvenile salmonid food resources can be evaluated.
- Bird survey (1995). The Port (Pentec Environmental, Inc.) will document land birds using the berm and water-oriented birds using the protected embayment.
- Coastal geomorphology. The COE will survey the physical integrity of the berm in 1995 and 1997. This will add to information gained from earlier surveys of elevations immediately post-placement (April, 1990) and in post-placement Years 1 and 2.

ACKNOWLEDGMENTS

The Port of Everett and the U.S. Army Corps of Engineers, Seattle District, have provided logistical, technical, and field support for this project. We would like to acknowledge Wilber E. Ternyik of Wave Beach Grass Nursery in Florence, Ore., who provided the nursery plants; the many state and federal agency representatives who volunteered to assist with the transplanting; and Dr. Ron Thom (Battelle Northwest) for the original design of the vegetation experiment and for technical advice on habitat development in urban estuaries.

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FIELD SURVEY AND CLASSIFICATION OF PUGET SOUND NEARSHORE HABITATS

Allison R. Bailey, Elizabeth Lanzer, and Thomas F. Mumford, Jr.[1]

INTRODUCTION

Loss of habitat in the nearshore marine and estuarine areas is one of the greatest threats to the Puget Sound ecosystem (British Columbia/Washington Marine Science Panel, 1994, and Puget Sound Water Quality Authority, 1990). The real implications of this habitat loss become apparent through the loss of habitat function, such as the decrease in food and nesting area for migratory birds. However, historic habitat loss in Puget Sound is difficult to determine due to the lack of a common classification system (Levings and Thom, 1994).

A good habitat classification system provides a common language to link physical description and biological function. The working assumption of most ecological classifications is that the physical characteristics of an area will determine the biological community that lives there. Ideally, if a classification adequately identifies the determinant physical parameters, one can predict the biological community from the physical characteristics or one can predict the physical characteristics from the biological community. Achieving this ideal is hindered by the fact that: (1) the natural world consists of continua of physical parameters and biological communities that must be arbitrarily divided, and (2) measurement of an exhaustive set of physical parameters may be impractical or impossible. Therefore, "an effective classification must weigh ecological reality (and complexity) against the need to remain tractable" (Dethier, 1990).

This paper describes the first large-scale field application of "A Marine and Estuarine Habitat Classification System for Washington State" (Dethier, 1990). Using data collected for the Puget Sound nearshore habitat inventory (described in Mumford et al., 1992), we can evaluate the Dethier habitat classification from three perspectives:

(1) How easily and consistently can the classification be applied in the field?

(2) Does the classification identify and describe all the unique biological communities in the marine and estuarine areas of Washington?

(3) How well does the classification link physical characteristics (habitat) and biological communities? Is it predictive?

HABITAT CLASSIFICATION SYSTEM

We used Dethier's (1990) "A Marine and Estuarine Habitat Classification System for Washington State" to classify field data sites by habitat type. Dethier's classification system was developed for two primary purposes:

(1) to serve as a framework for existing data and future inventory work on the exemplary marine and estuarine communities in the state, and

(2) to provide ecologically based mapping units and uniform terminology for marine and estuarine habitats.

The Dethier (1990) classification system is a hierarchical system that is compatible with the widely used wetland classification system developed by Cowardin et al. (1979) for the National Wetlands Inventory. The most notable alterations from the Cowardin system include the addition of a level for energy (wave and currents) and the addition of a substrate level for all habitats, not just unvegetated

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habitats. Dethier also includes lists of diagnostic and common species occurring at each common habitat type in Washington state. Figure 1 shows the structure of the Dethier classification system.

FIELD DATA COLLECTION

Field data was collected at 1,599 sites around Puget Sound, Washington, during May through September of 1991, 1992, 1993, and 1994 (see Figure 2 for the locations of all field data sites).

The primary purpose of this data was to assist in image processing and to verify the accuracy of final maps produced from multispectral imagery as described in Mumford et al. (1992). General locations for field surveys and specific field sites were chosen for that purpose. However, a secondary purpose was to categorize each site according to the Dethier (1990) habitat classification system.

For most sites the sampling unit was a circle with a diameter of 15 meters (corresponding to a 3 by 3 pixel area on the image data). We located the center of the circle using a differential Global Positioning System (GPS) unit. At each site we recorded:

- general information: date, time, name of USGS 7.5 minute quadrangle, general verbal description of plot and surroundings;
- physical characteristics: beach slope, approximate tidal height of plot center, and Dethier habitat classification (system, subsystem, substrate type, energy level, soil salinity); and
- biological characteristics: vegetation species and cover class (groupings of percent cover), and presence of other organisms.

We focused our data collection effort on the surface features (physical and biological) that would influence the interpretation of the imagery. We did not dig for organisms in the substrate. At each site we took 35mm color slides looking in eight cardinal directions from the center of the circular plot. We also took one or two slides showing an overview of the site and its surrounding area.

For some sites, we circumnavigated a feature (such as a kelp bed or a sand flat) or we delineated the line between two features with the GPS unit. For these sites we recorded the feature type and the Dethier habitat classification. We took one or two color slides showing the site and surrounding area.

TABULAR AND SPATIAL DATABASE

To facilitate analysis, the data collected during field surveys is stored in a digital database and a Geographic Information System (GIS). The tabular data is stored in nine related database tables. Each site has a unique site number, which relates the information from one table to another. The data, such as species names and habitat type, are stored as codes, and the translations of these codes are stored in separate tables. All GPS site locations (1,565 sites) are stored in a GIS and can be associated with the tabular information. The habitats described by Dethier (1990) and their associated species lists are stored in two related database tables. For both the field data and the Dethier classification files, each level of the classification (as shown in Figure 1) is stored in a separate column to allow analysis of each level separately or in combination with other classification levels.

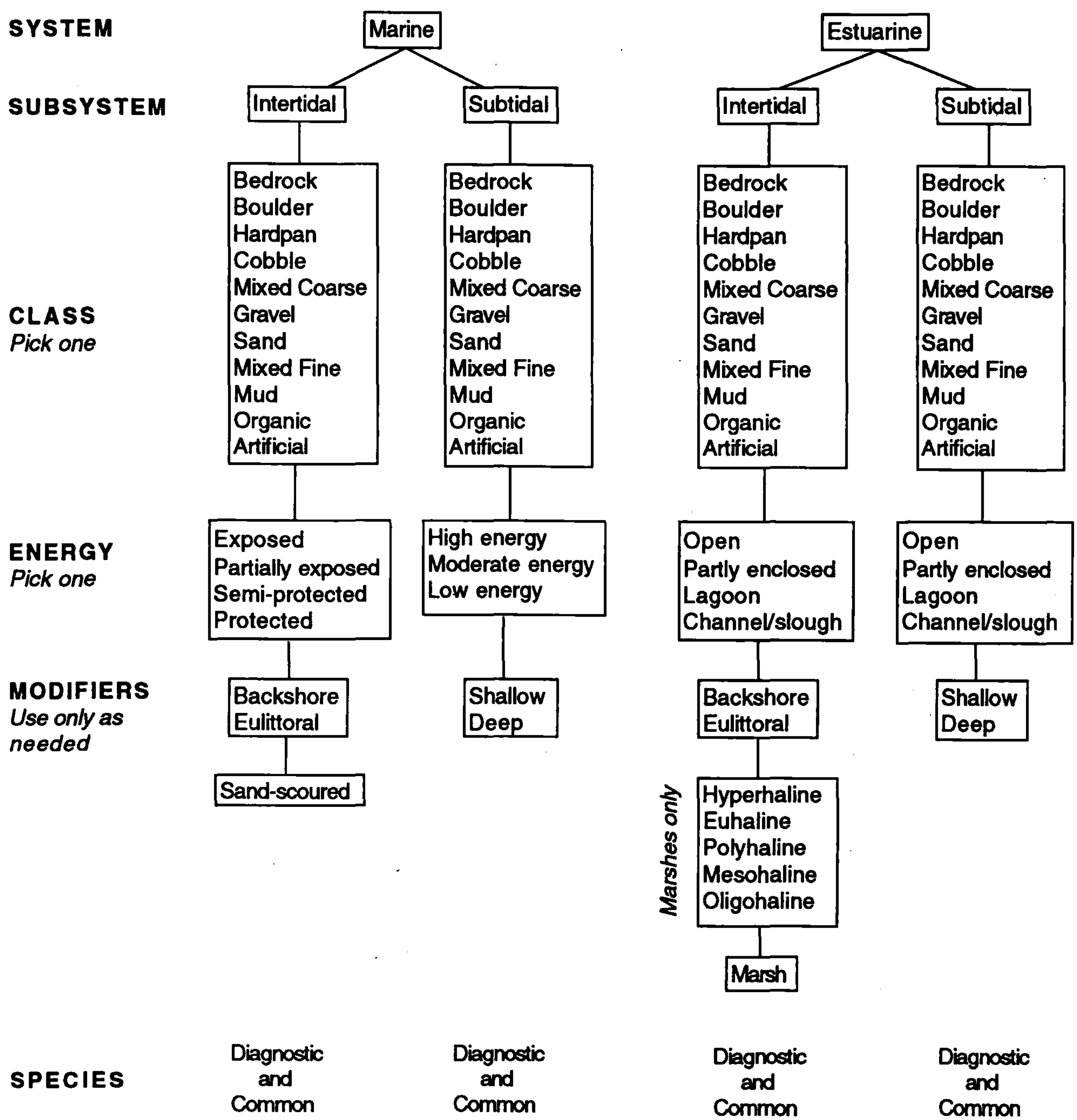
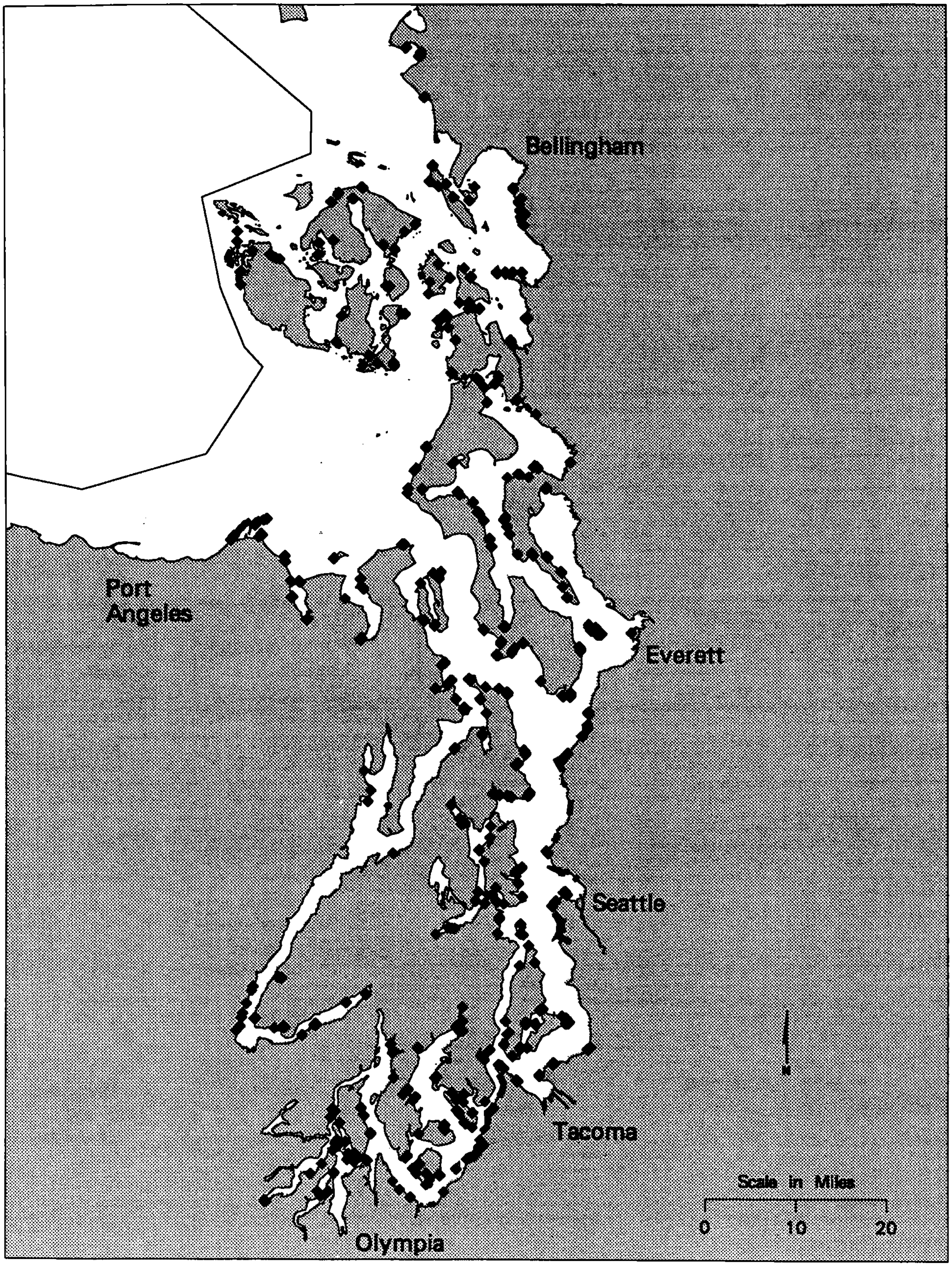


Figure 1. Structure of Dethier's (1990) "A Marine and Estuarine Habitat Classification System for Washington State"


Bellingham
Port
Angeles
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Seattle
Tacoma
Olympia
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Scale in Miles
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Figure 2.

EVALUATION OF DETHIER CLASSIFICATION SYSTEM

Field Application of Classification System

Biologists found the Dethier classification system easy to use in the field. The categories were comprehensive and appropriate for the scale of our sampling unit, a 15-meter diameter circle. The categories were generally well defined, but required some fine tuning to apply them consistently in the field.

- System and subsystem: The first two classification levels, system and subsystem, are geographically defined and therefore easy to determine.
- Class (substrate): Most disagreement between biologists occurred over the substrate classification. To address this problem, we recorded the cover class (groupings of percent cover) of each substrate grain size in the circular plot, and then assigned the final substrate type based on numerical rules. These numerical rules agreed with crew members' preliminary assessment of the substrate for 87 percent of sites. This level of agreement was considered acceptable, and to promote consistency the numerical rules were used to assign the final substrate name.
- Energy: Energy level was the most subjective parameter of the classification. We used Dethier's "sites surveyed" list as examples for each energy level and assessed the energy level of a specific site based on those examples.
- Depth: The depth modifier is geographically defined; therefore, it was relatively easy to determine.
- Water chemistry (salinity): The soil salinity measured at salt marsh sites was used only as a guide for assigning a water chemistry modifier. Because salinity measured at one point in time is not always a true measure of the general salinity regime, the plant community was used as the definitive indicator of the appropriate water chemistry modifier for a site.

Identification of Unique Biological Communities in Washington State

Dethier (1990) describes 67 unique biological communities that occur in 104 different marine and estuarine habitats in Washington state. Habitats are lumped together when the biological communities are not distinct; for example, "Marine Intertidal Sand: Exposed and Partially Exposed" has one list of species although it describes two different energy levels. Therefore, using this classification system, we do not expect a unique combination of physical parameters always to predict a unique community of organisms. We do, however, expect the classification to describe all of the unique biological communities that are found in Washington state and the habitat or habitats in which they occur.

We found 95 unique habitats during our field surveys. Of these habitats, 67 are not listed by Dethier (1990). Because identifying unique biological communities is the primary purpose of the classification, we will evaluate the importance of these new habitats by comparing our species lists to Dethier's and looking for significant differences. If a community is not significantly different from one described by Dethier, the new habitat in which it occurs will be lumped with the habitat(s) that most closely identify that biological community.

We have begun to evaluate the significance of the 67 new habitats. Four of the new habitats describe a biological community not identified by Dethier—the backshore spit or berm. These areas are not regularly inundated by tides, but receive salt influence from spray or extreme high tides. The substrate is usually sand or gravel, and drift logs are often present. *Elymus* sp. (dune grass), *Grindelia* sp. (gum weed), *Achillea* sp. (yarrow), and *Ambrosia* sp. are common plants in these habitats. The center of Dungeness Spit is an example of a spit/berm habitat. Because these areas have a significantly different plant community from other habitats in the classification, and because they are an integral part of the nearshore ecosystem in Puget Sound, it is reasonable to add a new biological community and habitat modifier to the

classification. These areas are classified as usual (system, subsystem, substrate, energy, water regime) with "spit/berm" as a modifier.

The remaining 63 new habitats have not yet been evaluated for unique biological communities.

Linking Physical Characteristics (Habitats) and Biological Communities

Dethier's classification describes marine and estuarine habitat types and lists of species that are characteristic of those habitats in Washington state. "The hierarchy of physical factors used in this classification should provide reasonable predictability of dominance types" [biological communities] (Dethier, 1990). We can test the capability of the classification to link physical characteristics and biological communities using our site-specific data on habitat type and species composition.

To test the predictive capability of the classification we compared the actual (field-assigned) habitat to the habitat predicted by Dethier's classification based on the species composition of a site. For each site, we found the Dethier habitat or habitats that had the most species in common with the site's species list. We then compared the habitat (or habitats) with the most matching species to the actual habitat determined in the field (see Figure 3).

After a preliminary comparison of 1,557 sites (sites with species occurrences), the predicted habitat matched the actual habitat for 247 sites. These 247 sites are from a variety of habitat types and are distributed throughout Puget Sound, so the classification appears unbiased. As the next step in this analysis, we will evaluate how many of the sites that did not match were from habitats with no corresponding Dethier habitat (the 67 new habitats mentioned above).

Some additional analyses will be used to evaluate the strength of the link between physical characteristics and biological communities using the Dethier classification. These analyses include: (1) the comparison described above using species lists grouped by habitat type, and (2) the use of multivariate analysis to group our sites according to species composition and comparison of these groups to their physical characteristics and to the biological communities described by Dethier.

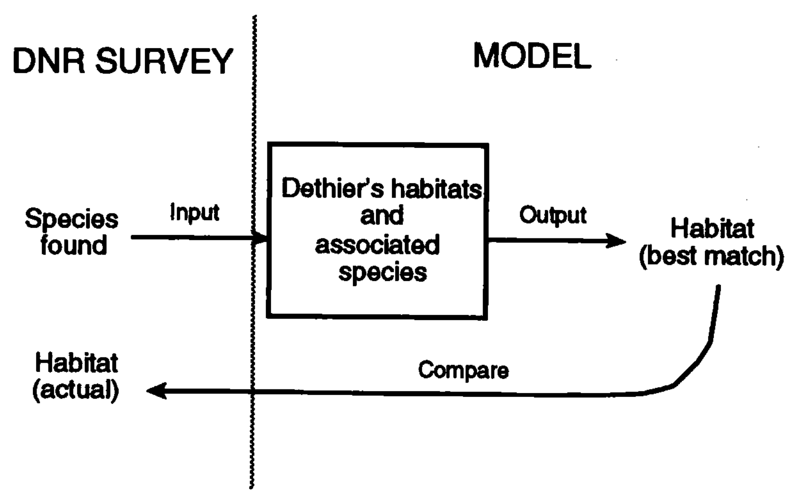

Figure 3. Procedure for comparing actual habitat to habitat predicted by Dethier's classification based on species composition

CONCLUSION

We recommend use of the Dethier classification as a common system for describing marine and estuarine habitats in Washington state. It is an easily applied system that accounts for the most significant differences between biological communities. Through our continued evaluation of the classification with site-specific data, we will update or modify the system as necessary. The system needs testing in additional locations, including the Strait of Juan de Fuca, the outer coast of Washington, and subtidal habitats. Additional physical parameters, such as beach aspect or source of sediment, may increase the predictive power of the classification. Nonetheless, the Dethier classification provides a minimum level that can be used to promote consistency in habitat description. This consistency will provide the essential foundation for research and resource management applications, such as determination of habitat loss and habitat function.

ACKNOWLEDGMENTS

Terrie Manning, Betty Bookheim, and Kimiora Ward provided invaluable assistance as primary field crew members. Becky Ritter and Betty Stephens produced maps for field work, provided GPS support, assisted with field work, and contributed to the mental well-being of the field crew. Many folks within DNR volunteered a week of their time to assist with field work and made the work enjoyable by providing a fresh perspective. Larry Holt gave us a "jump start" on the use of GPS. Andy Hess and Tony Morris allowed us access to data from the EPA's base station. Kathleen Bailey provided technical assistance and moral support for database programming and analysis. Bruce Dahlman developed maps for this manuscript and presentation. Many thanks for all the support.

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WETLAND MITIGATION IN MARYSVILLE, WASHINGTON, USING AN HISTORIC ESTUARINE WETLAND

Jonathan H. Ives, Mark Matthies and Sarah Cassatt[1]

INTRODUCTION

Background and Project Need

In November 1994, the City of Marysville completed construction of wastewater treatment improvements at its existing wastewater treatment facility located at the south end of Marysville, adjacent to Ebey Slough in the Snohomish River Estuary (Figures 1 and 2).

Improvements were necessary to handle future projected wastewater treatment needs. The improvements were designed to bring the treatment facility into compliance with Washington Department of Ecology regulations for the wastewater treatment and effluent discharge (Hammond, Collier & Wade-Livingstone Associates, Inc., 1991).

Construction of the proposed wastewater facility improvements required the placement of fill on 3.0 acres of wetland, and temporary impacts to 0.92 acre of intertidal wetlands for construction of the effluent outfall to Ebey Slough. Approximately 0.3 acre of wetland was filled for the new sewage headworks and 2.7 acres for the sand filtration and other effluent treatment facilities (Figure 3; Table 1).

Table 1. Wetland acreage affected by proposed action — City of Marysville wastewater treatment plant expansion

Cover Type	Treatment Facility Acreage	Steamboat Slough Outfall Feet	Steamboat Slough Outfall Acreage
Emergent marsh[a]	3.00	375	0.60[b]
Mudflat[a]	--	90	0.15[b]
Open water[a]	--	350	0.16[c]
Shrub/Scrub[a]	--	25	0.01[c]
Grass/Shrub	0.23	--	--
Existing fill/roadway[d]	0.13	1,860	0.85[c]
Total area impacted	3.36	2,700	1.77
Total wetland acreage	3.00	--	0.92

[a] Wetland areas
[b] Assumes 70-foot wide construction corridor
[c] Assumes 20-foot wide construction corridor
[d] Construction on top of existing lagoon dike

[1] Jones & Stokes Associates, Inc., 2820 Northup Way, Suite 100, Bellevue, Washington 98004-1419, 206/822-1077.

MITIGATION ALTERNATIVES

In the absence of a wetland ordinance for the City of Marysville, improvements to the wastewater treatment facility were evaluated in relation to Ecology's Model Wetland Ordinance (Washington Department of Ecology, 1990).

Because of its location behind dikes within an estuary, the Marysville treatment facility is surrounded by wetlands on all sides. Complete avoidance of wetlands was therefore not possible without moving the entire treatment facility to a new upland location.

Recognizing that limitation, emphasis therefore was placed on minimizing the impact of the project on wetlands and compensating for affected wetland areas. This was accomplished by selecting the onsite project alternative that would have the least impact on wetland resources. Two alternatives of transporting wastewater offsite to the City of Everett treatment plant via pipeline were not considered feasible because of cost. Two other onsite alternatives were determined to impact greater wetland acreage (Jones & Stokes Associates, 1990, 1991).

Five potential mitigation sites were investigated, and a feasibility analysis was conducted to select the most appropriate site. Elements considered in the feasibility analysis included location, existing conditions, potential impact on existing sensitive areas, cost, and time constraints.

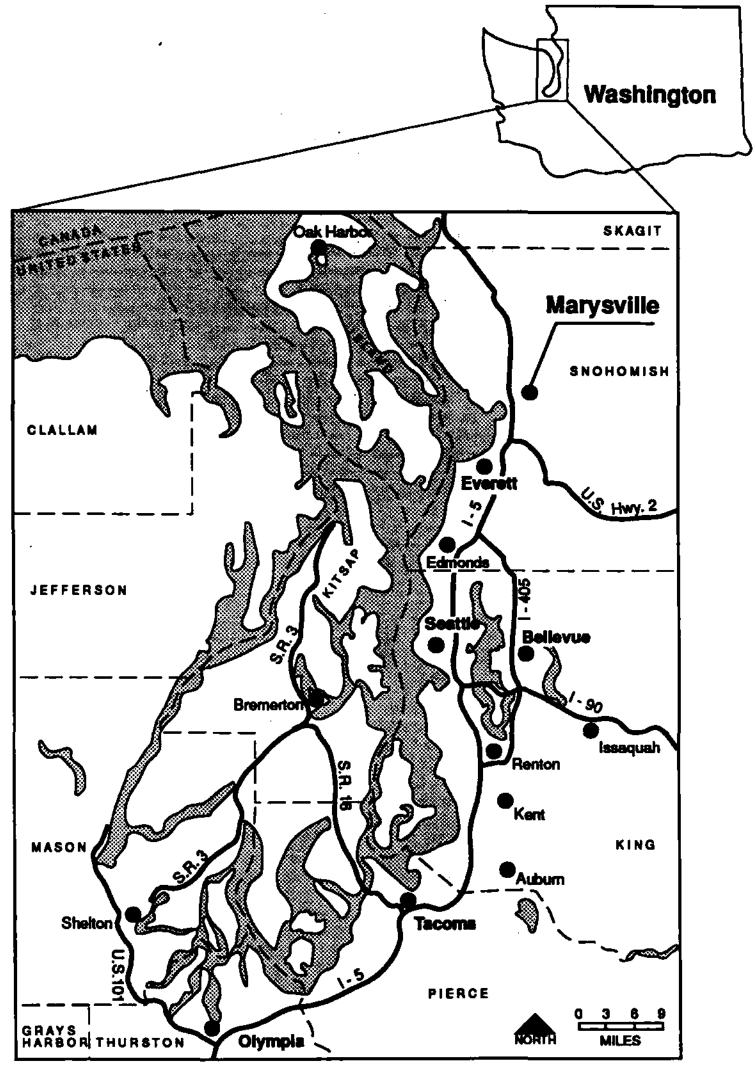

Figure 1. Location map of Marysville, Washington

The chosen site was a portion of the Regan property consisting of approximately 34 acres of grassland pasture located east of the sewage treatment facility, and immediately north and east of Ebey Slough (Figure 2). The area was hydrologically isolated from Ebey Slough by a flood control dike constructed during the late 1800s.

Based on the 1989 *Federal Manual for Identifying and Delineating Jurisdictional Wetlands* (Federal Interagency Committee for Wetland Delineation, 1989) and the Corps directive regarding agricultural land (Seattle District U.S. Army Corps of Engineers, 1990), the land met the definition of a wetland, although it was planted with a grass seed mix and harvested annually for silage. This site was selected as the preferred mitigation site for several reasons: its location adjacent to Ebey Slough and a tidal water supply; low existing wetland functional values and disturbance by ongoing agricultural activities; elevations and soil conditions suitable for intertidal wetlands; and close proximity to the wetland impact area.

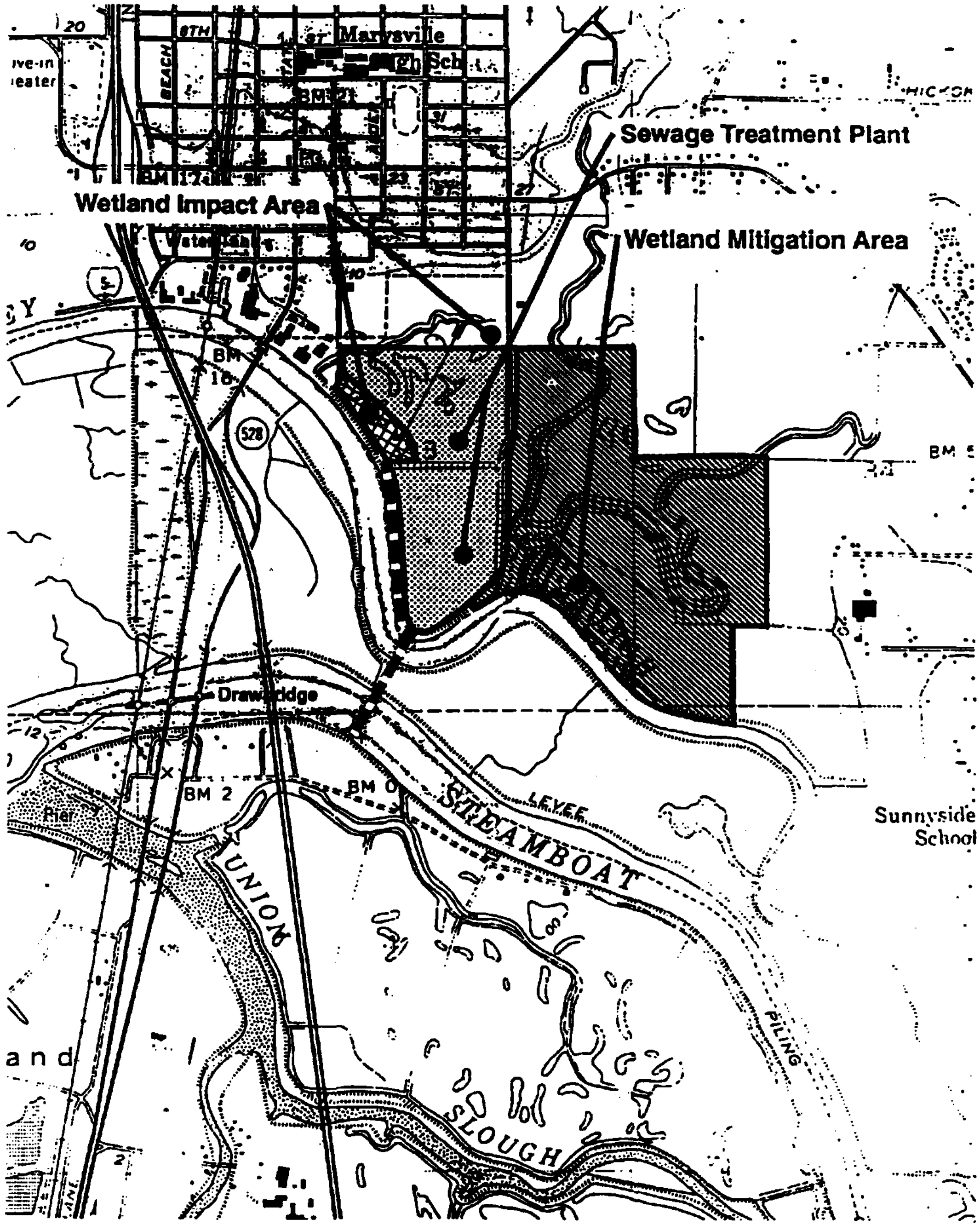

Figure 2. Wetland mitigation area, Marysville wastewater treatment plant

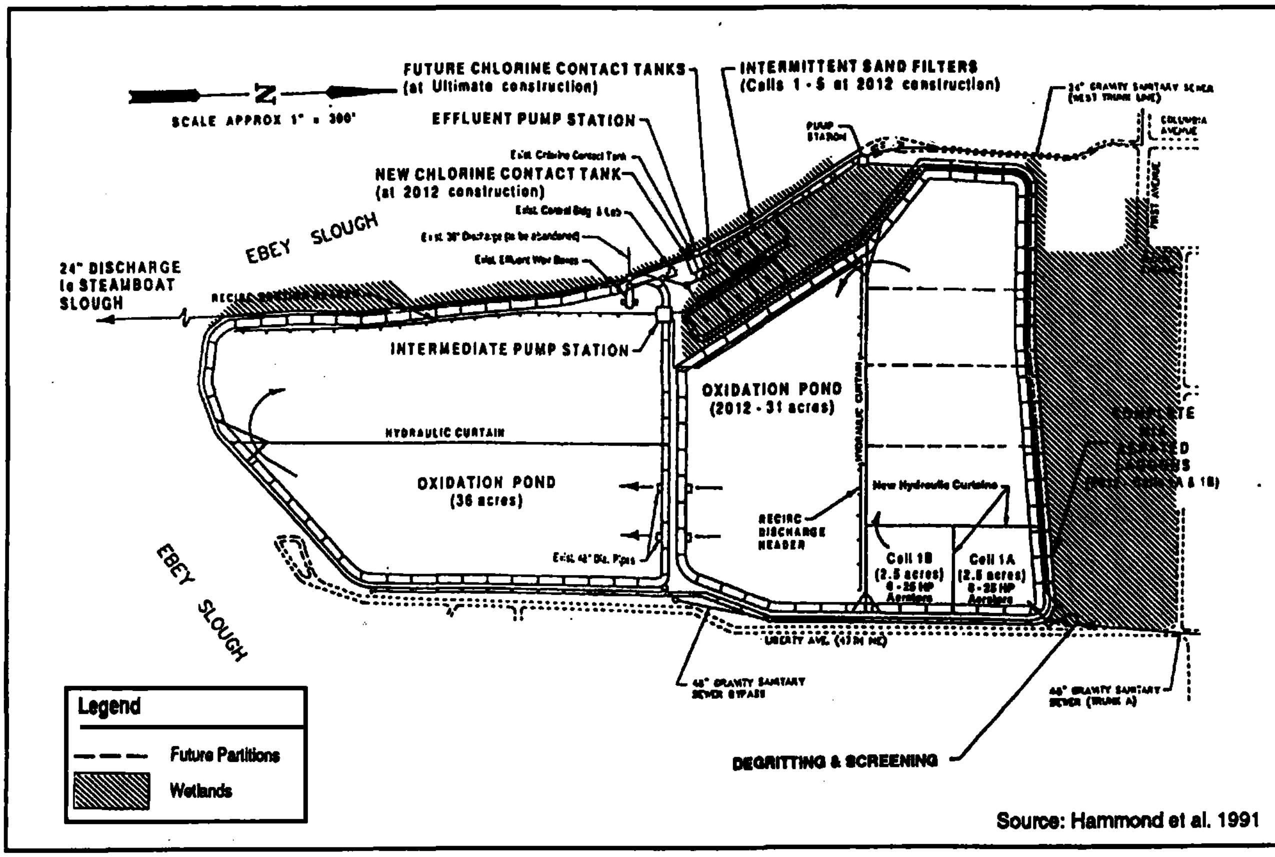

Figure 3. Proposed wastewater treatment expansion facilities and wetlands, City of Marysville, Washington

Concepts for Enhancing Wetlands at the Preferred Site

Five concepts for enhancing the Regan property were evaluated in the wetland mitigation plan.

Concept 1—enhance existing wetland through planting

This concept would have involved increasing the vegetative diversity of the site by planting native trees, shrubs, and possibly herbs. This concept was rejected because it was not certain that sufficient water would exist to support a more diverse wetland community during the growing season. It was also possible that aggressive, invasive species, such as reed canary grass (*Phalaris arundinacea*), soft rush (*Juncus effusus*), and Himalayan blackberry (*Rubus discolor*), would overtake the site.

Concept 2—alter freshwater regime behind dike and enhance site with planting

This concept was to be accomplished by altering runoff patterns from the watershed, runoff that passes through Allen and Wood's creeks and is discharged at low tide through tide gates into Ebey Slough. This concept was rejected because the hydrologic regime and supply of water would be extremely variable due to seasonal variations in runoff. Also, the uncertain and highly variable water regime made it difficult to predict the type of wetland that would develop.

Concept 3—remove tide gate and enhance wetland through planting

This concept would have been accomplished by opening the tide gate to allow tidal flow from Ebey Slough into and out of the proposed site. This concept was rejected because the narrow opening at the tide gate would result in a damped tidal cycle in the wetland with less water circulation. In addition, it would have been difficult to hydrologically isolate the mitigation site from other portions of the Regan property.

Concept 4—remove part of dike

This concept would have involved the removal of approximately 400 linear feet of flood-control dike immediately east of the tide gate at Wood's Creek. This concept was selected as the most feasible of the five concepts evaluated.

Concept 5—remove outboard dike along Ebey Slough

This alternative would have involved removing the entire Ebey Slough dike along the south side of the Regan property and constructing a dike inland, adjacent to Wood's Creek. The entire site would become directly connected with Ebey Slough. This concept was rejected because of the potential flood hazard to adjacent properties.

WETLAND DESIGN AND CONSTRUCTION

Features of the mitigation plan included:

- reestablishing 13.5 acres of estuarine wetland in an area that was historically wetland,
- removing 400 linear feet of existing dike on the southwest end of the site,
- constructing 1,900 linear feet of new flood-control dike inboard of the existing dike along Ebey Slough,
- excavating shallow channels to connect low-elevation areas as a measure to minimize fish stranding, and
- planting approximately 0.9 acre of dike and side slopes of the new and existing dikes with Sitka spruce and preferred shrubs.

Construction of the flood control dike and fish channels was completed in January 1994. The 400 feet of outboard dike was removed in March 1994, and tidal flooding returned to the site.

Hydrology

A hydrologic model was developed to determine tidal conditions on the mitigation site (Figure 4). Assuming an average ground elevation of 0.5 feet, the mitigation site would be inundated approximately 50 percent of the time and would be covered by approximately 2 feet of water about 30 percent of the time.

Vegetation

The vegetation element of the proposed mitigation program involved natural revegetation of the estuarine wetland portion of the site (13.5 acres) and planting of shrubs and trees on the flood control dike.

As part of this study, the elevations of plant communities were surveyed on north Ebey Island (an adjacent dike-breached estuarine wetland). A range of elevations at which estuarine plant species were found is shown in Figure 5. These data are based on a limited number of spot elevations. Figure 5 shows that Lyngby's sedge (*Carex lyngbyei*) is the dominant plant species at very low and mid-elevation ranges (-1.0 to 4.0 feet mean sea level [MSL]). Hardstem bulrush (*Scirpus acutus*) and common cattail (*Typha latifolia*) were found growing at middle to high elevations (3.8 to 5.0 feet MSL). Other high marsh wetland species were found growing at middle to high elevations. The range of elevations on the mitigation site is -0.9 to 3.0 feet MSL. Based on the previously mentioned survey results, this range of elevations would most likely support a community dominated by Lyngby's sedge. Hardstem bulrush and common cattail would probably be commonly interspersed within the sedge community at mid-range elevations.

MONITORING REQUIREMENTS

Performance standards will form the basis for assessing the yearly progress of the mitigation and for determining whether the project is successful at the end of the monitoring period.

The length of time for mitigation compliance at this site will be 10 years. This period will allow for the natural development of an estuarine wetland which, based on analysis of present conditions on Ebey Island, should include a mix of Lyngby's sedge, common cattail, hardstem bulrush, and mudflat. Based on studies by Frenkel and Morlan (1990), complete reestablishment of the site as an estuarine wetland is expected to take approximately 10 years.

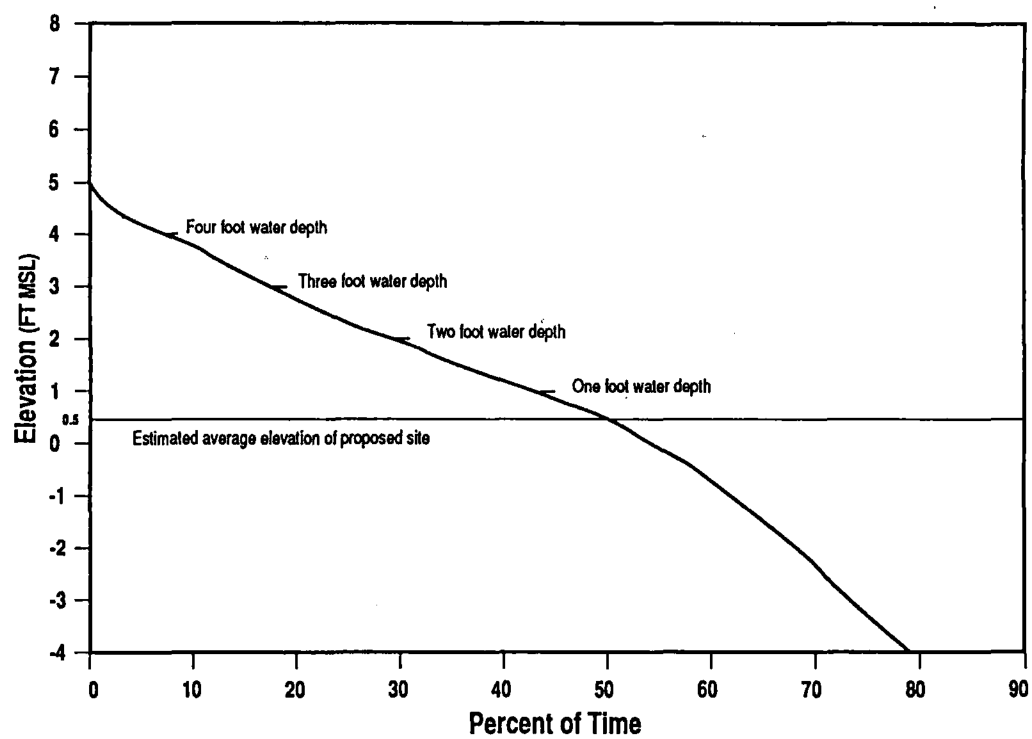

Figure 4. Percent of time during which tide heights are estimated to exceed elevations relative to mean sea level (MSL)

Performance standards defined by Ecology in the 401 Water Quality Certification (Public Notice No. 91-2-00162) include: (1) year 1—presence of emergent plant seedlings in the estuarine wetland and year 10—viable estuarine wetland; (2) removal and control of invasive and exotic species (e.g., reed canary grass and purple loosestrife [*Lythrum salicaria*]) to a dominance of less than 10 percent areal cover throughout the monitoring years; (3) 50 percent vegetative cover in areas above mean higher high water by year 3 and thereafter; and (4) 80 percent survivability of planted trees and shrubs by year 5.

The monitoring includes four elements: vegetation, wildlife, fish, and water quality. Data for vegetation cover and plant species richness are collected from randomly placed, square-meter plots on a series of transects in the mitigation site. Wildlife use is monitored using point-counts and transects. Fish

were sampled using a seine net during high and low tides. Water salinity data are collected from identified points located along the vegetation transects.

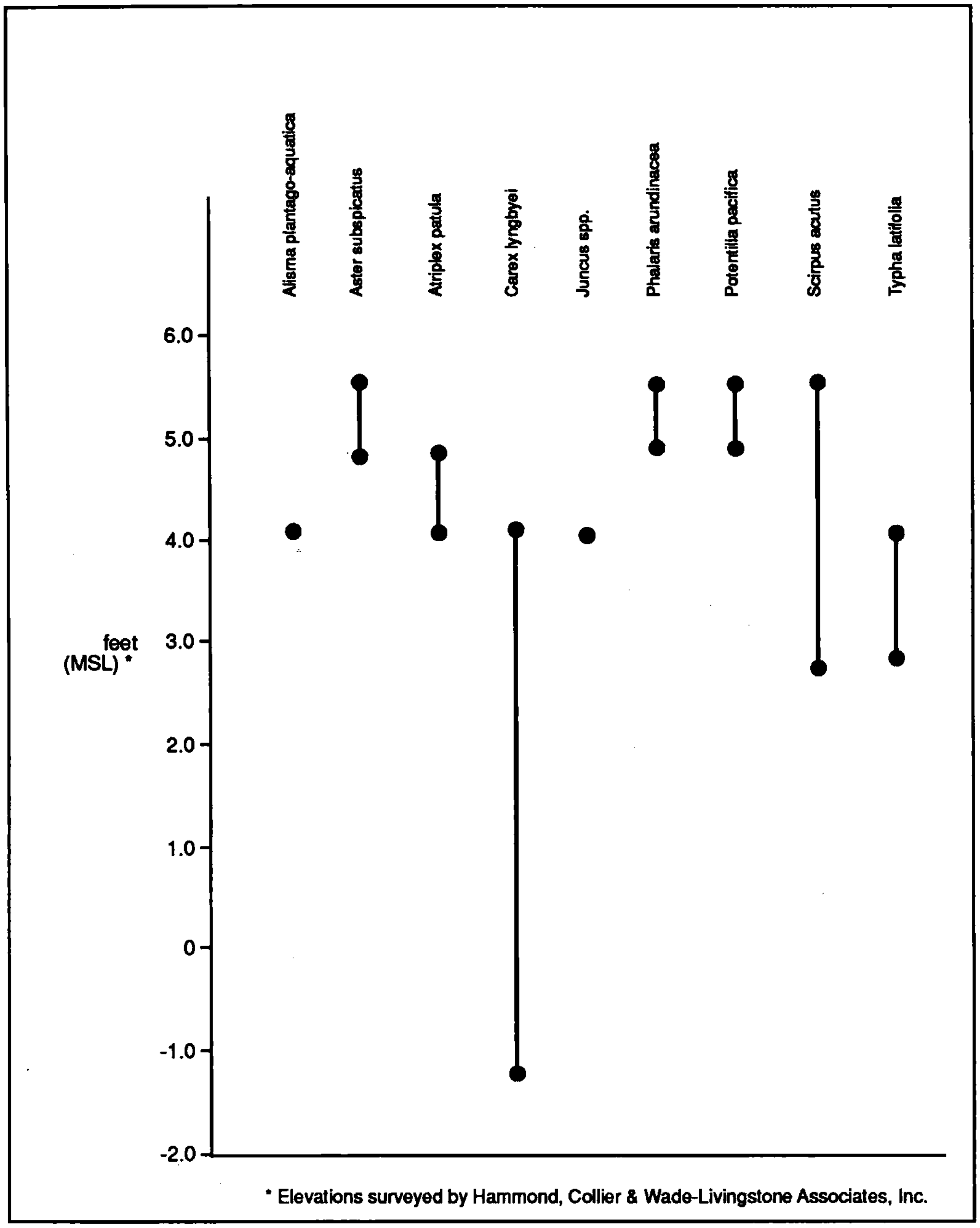

Figure 5. Range of elevations of plants growing in Ebey Island and Ebey Slough, Snohomish River Estuary

MONITORING RESULTS TO DATE AND PROJECTED RESULTS

Revegetation of the estuarine wetland portion of the site is occurring by natural establishment of emergent plants rather than through a planting program. The natural establishment method on diked wetlands has proven to be more successful than de novo marsh creation (Frenkel and Morlan, 1990). In addition, seed stock from vegetation on Ebey Island and along Ebey Slough and residual seed within the

mitigation site represent a significant reservoir of emergent plant seed material. Reestablishment of the site as an estuarine wetland will be an evolving process that may take up to 10 years to complete (Frenkel and Morlan, 1990).

Year 1 (1994)

Vegetation

While vegetation was expected to change dramatically immediately following dike removal, monitoring during the first four months following dike removal showed a slow decline in vegetative cover, and more dramatic die-off during the following three months. By September 1994, most of the upland plant species and grasses present as part of the previous agricultural practices died due to exposure to tidal inundation and brackish water. These species included perennial ryegrass (*Lolium perenne*), quackgrass (*Agropyron repens*), white clover (*Trifolium repens*), and dandelion (*Taraxacum officinale*).

During monitoring conducted in September 1994, approximately 56 percent of the site was bare mud and 44 percent was vegetated. Residual species have survived, including brass buttons (*Cotula coronopifolia*) and foxtail (*Alopecurus geniculatus*). Brass buttons and foxtail account for approximately 60 percent of the vegetation cover. Other species that have begun to seed on the site include common cattail, Lyngby's sedge, and hardstem bulrush.

Wildlife

Wildlife use during the first six months after dike removal has been dominated by waterfowl (American widgeon [*Anas americana*], Barrow's goldeneye [*Bucephala islandica*], and Canada geese [*Branta canadensis*]), shorebirds, and wading birds (dunlin [*Calidris alpina*] and sanderlings [*Calidris alba*]). Great blue herons (*Ardea herodias*) and northern harriers (*Circus cyaneus*) have also been observed.

Fish

In May the wetland was sampled with a seine net to determine fish use during high and low tides. Three-spine stickleback (*Gasterosteus aculeatus*) and juvenile salmonids (*Oncorhynchus* sp.) were found during high tide; only small (less than 1 centimeter) sticklebacks were found in the wetland during low tide.

Water quality

Water temperature and salinity were measured at five locations in the wetland channels in May and September 1994 during high tide events (+11.1 in May and +10.7 in September). The results of the sampling are presented in Table 2. During low river flow periods, saline stratification occurs at high tide in the wetland.

Water quality data (temperature and salinity) taken at the mitigation site and the adjacent Ebey Slough during low river flow periods indicate greater mixing than in the mitigation wetland.

Years 2 to 4 (Projected)

By the second year, permanent colonizers are expected to appear in greater numbers. Plants such as cattail, Lyngby's sedge, and hardstem bulrush will become dominant over time. Other common species likely to be permanent colonizers include rushes, Douglas' aster (*Aster subspicatus*), Pacific silverweed (*Potentilla pacifica*), and water parsley (*Oenanthe sarmentosa*).

Year 10 (Projected)

Based on the vegetative composition elsewhere in the estuary, after 10 years Lyngby's sedge may become the overall dominant species. At the Salmon River site, Frenkel and Morlan (1990) found that bare ground was dominant in the second year, but by the 11th year there was no bare ground.

Table 2. Water temperature and salinity of the wetland and Ebey Slough, Marysville, Washington

Sampling Date	Temperature (°C)		Salinity (o/oo)	
	Surface	Bottom	Surface	Bottom
Wetland				
May 1994 (11.1 MSL)				
Station 1 (mouth)	15	14.5	2.5	2.5
Station 2 (interior)	18	17.5	2.5	2.5
September 1994 (+10.7 MSL)				
Station 1 (mouth)*	16.5	17.0	9.5	11
Station 2 (interior)*	15.5	16.0	8.5	8.5-9.0
Ebey Slough				
September 1994 (+10.7 MSL)	17	16.5	11.5	12

* Temperature increase with depth was possible due to higher salinity at the bottom.

Salt marsh vegetation commonly has strong zonal expression reflecting gradients in elevation (tidal inundation) and salinity (Frenkel and Morlan, 1990; Hutchinson, 1989). Species diversity and net production have been found to increase with increasing elevation and to decrease with inundation period (Frenkel and Morlan, 1990; Eilers, 1979). Dominance of plants may be apparent in low elevations resulting from frequent and long inundation (Eilers et al., 1984).

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SPENCER ISLAND INTERTIDAL WETLANDS RESTORATION PILOT: BEGINNING THE TRANSITION TO WATERSHED MANAGEMENT

Jane Rubey[1]

Spencer Island is the largest tidal wetlands restoration project of its kind in Washington. It is a non-compensatory project serving as the first pilot action under the wetlands restoration element of the Puget Sound Water Quality Management Plan. This paper presents the rationale behind this non-compensatory action, the project objectives, and the technical issues that were addressed.

RATIONALE FOR NON-COMPENSATORY ACTION

It is recognized that non-compensatory wetlands restoration is crucial to meeting the goal of no net loss of wetlands. Existing planning and regulatory approaches have failed to prevent the loss of important ecological functions performed by wetlands. As we witness ecosystem degradation at a landscape scale, federal and state agencies are adopting a new management perspective of stewardship: applying non-regulatory actions and addressing resource management in a system-based or "watershed" context.

Maintaining the environmental processes and functions of watersheds requires integrating multiple resource issues and multiple players at the federal, state, and community level. This is the intent of the wetlands restoration element of the Puget Sound Water Quality Management Plan, adopted by the Puget Sound Water Quality Authority. In the plan, wetlands are recognized as valued systems to improve and maintain the water quality of the Sound.

Under the wetlands restoration element, the plan directs Ecology, USFWS, and EPA to implement early action pilot wetland restoration efforts that achieve one or more of the following:

1) to restore estuarine wetlands no longer utilized for agriculture, by removing dikes;

2) to restore wetlands currently degraded by non-point or point sources of pollution by addressing the causes of pollution; or

3) to address restoration through removal of exotic plant species.

The purpose of the pilot(s) is to begin interagency cooperation and problem solving to conduct proactive non-compensatory wetlands restoration actions. It seeks:

1) to demonstrate the feasibility of restoration techniques that rely primarily on natural processes;

2) to increase public awareness and provide education on the importance and functions of restored wetlands; and

3) to initiate interagency procedures for restoring wetlands in a system context, by defining agency and local sponsor roles along two planes of coordination—first, with federal and state agencies establishing the procedures and priorities for cooperatively supporting a longer-term restoration program, and second, getting mechanisms that foster local participation and stewardship.

THE SPENCER ISLAND PILOT

In 1991, the Environmental Protection Agency (EPA), the U.S. Fish and Wildlife Service (USFWS), and Washington Department of Ecology (Ecology) began a partnership to conduct a pilot wetlands restoration effort within the Puget Sound. EPA's Puget Sound Estuary Program contribution of $125,000 initiated the effort.

At the time a number of factors converged to convince these agencies to agree to work in the lower Snohomish River.

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1) Approximately 12 thousand acres of wetlands existed in the Snohomish estuary before 1884, but this amount had decreased to some 18 hundred acres by 1977. As a result, the lower Snohomish River is experiencing a number of watershed scale problems, including loss of flood buffering capacity, loss of critical salmon rearing areas, declining waterfowl production, competing uses of open space areas, and irreversible loss of valuable natural resource lands to urban development.

2) Because the county and state were able to purchase a number of properties within the lower watershed in past years, there were numerous short- and long-term opportunities for restoring extensive areas of floodplain and wetland habitat. Linkages between existing public acquisition efforts and a watershed-wide restoration program could easily be made to align public open space, habitat protection, and hydrologic management interests.

3) Also, Snohomish County was a very receptive and energetic local sponsor for the project.

South Spencer Island, which we refer to as Spencer Island, is located about 1 mile east of Everett, in the lower Snohomish River system. It is situated between Union and Steamboat sloughs approximately at river mile 3.5. During normal river flow these sloughs are dominated by tidal actions.

Spencer Island is 414 acres in size and is isolated from the river by a 10-foot dike constructed mainly of wood waste. A network of drainage channels with exterior culverts and tide gates was constructed to drain the island for agricultural purposes.

The land is fairly flat, and averages 1 to 2 feet MSL throughout most of the island interior. Current elevations are a result of an estimated 4 feet of subsidence caused by the diking and draining. While the dike prevented tidal inundation of this former estuarine wetland, tide gates allow sufficient water on the island to create palustrine wetland conditions.

Inside the dike, the area is dominated by marsh containing dense monotypic stands of reed canary grass (*Phalaris arundinacea*). Also present are lower, wetter areas dominated by cattails (*Typha spp.*) and soft rush (*Juncus effusus*). Permanently flooded drainage ditches and excavated ponds, many with submergent vegetation, dot the island. Higher areas of the island grade from scrub-shrub wetlands with blackberry and rose (*Rosa spp.*) to forested areas with mixed stands of willow (*Salix spp.*), red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), and Sitka spruce (*Picea sitchensis*).

Palustrine emergent wetland is the most common wetland class covering nearly 60 percent of the island. The next most common is palustrine forested and palustrine aquatic bed.

In 1989, the island was purchased by Snohomish County and Washington Department of Fish and Wildlife (DFW) and taken out of agricultural use. The DFW purchased the northern half of Spencer Island with funds raised through the Duck Stamp Program, and manages the area for waterfowl production. This portion of the island provides high quality breeding habitat for waterfowl game species.

Snohomish County purchased the southern half of Spencer with assistance from the Washington Department of Natural Resource's Aquatic Lands Enhancement Account. Snohomish County Parks intends to use the southern portion for public access and education. From the inception of the project, the specific management needs of each owner required a balancing of resource management issues on the site:

1) DFW's major concern was protection and enhancement of waterfowl breeding conditions, which required stabilizing water levels while increasing water flushing. Improved water control would serve to protect nesting sites, better control reed canary grass, and improve water quality by increasing dissolved oxygen levels and lowering water temperatures and eutrophication.

2) Snohomish County desired that passive public use and interpretation be provided, while minimizing maintenance costs associated with the project.

3) Agency restoration proponents sought to achieve several ecological objectives:

a) reestablishing tidal conditions to approximately 50 acres of historic tidal wetland (thus increasing habitat diversity and returning a depleted intertidal wetlands habitat type to the system);

b) displacing the current monotypic reed canary grass stands with native tidal wetland plant communities; and
c) providing an increase in overwintering habitat for juvenile salmonids and other estuarine fish species.

To meet all of these management needs, the pilot project was divided into separate, yet integrated, northern and southern components, which both:

1) restore approximately 50 acres of southern Spencer Island to tidal influence by breaching the exterior dike, and

2) enhance approximately 350 acres of northern Spencer Island palustrine wetland system by constructing water control structures in the form of a cross levee and improved culvert system.

TECHNICAL DESIGN OF THE PROJECT

Once consensus was reached regarding the overall project approach, the real challenge of designing the project began. Numerous scientific and technical hurdles had to be overcome in the design of site actions that would achieve the objectives of:

1) managing water levels in northern Spencer;

2) reestablishing tidal conditions to southern Spencer;

3) reestablishing native intertidal plant communities;

4) increasing habitat attributes for juvenile salmonids; and

5) monitoring site changes.

1) To manage water levels in northern Spencer, the cross levee was constructed to restrict tidal inundation to the south project area. The height necessary to prevent overtopping during regular tidal cycles was calculated by Snohomish County Public Works Department using computer models of hydrologic conditions in Union and Steamboat sloughs.

The March tide sequence was used in the model as it represented maximum tide heights during spring nesting season, the period of greatest need for stable water levels. The levee height was designed that high tides would not overtop it with enough frequency or depth to inject large amounts of water into the nesting habitat. In addition, the November floods in 1990 were modeled to assess the effect of floods on potential levee configurations. These floods were 15-and 80-to 120-year flood events.

In conjunction with the modeling, a geotechnical analysis was conducted to determine the feasibility of a cross levee and what structure and location would work. Two primary geotechnical concerns were the presence of soft compressible soils in the shallow subsurface and the high water table. To address these concerns, the 2,300-foot levee structure consisted of a light wood waste core with a native soil cap. Both these materials were obtained on site—the wood waste from a stockpiled area near the exterior dike, and the native soil a clay material from the wetland.

Modeling determined that the levee elevation should be 9.0 ft. MSL with a 400-foot wide spillway at 8.0 ft. The levee would have 3-foot to 1-foot front and backslopes, and 5-foot to 1-foot slopes at the spillway, to reduce erosion. Extreme high tide was predicted at approximately 12.5 ft MLLW; thus the levee would not be overtopped during regular tidal floods. The levee was designed to overtop during periods of river flooding primarily in late fall and early winter months. To allow for fish access to northern Spencer, two 60-inch culverts, each containing control weirs, were included in the cross levee.

To facilitate the flushing of northern Spencer, three culverts in the exterior dike were replaced. The hydrologic modeling indicated that appropriate culvert sizes were 36-in. and 48-in. diameters. Culverts were installed at an elevation of 2 to 3 ft. MSL. To provide a workable control structure for maintenance of stable water levels, flash board risers were attached to the interior end and "barn door" gates for fish escapement to the exterior end.

2) Reestablishing tidal conditions to the 50 acres in southern Spencer also required hydrologic modeling to determine appropriate dimensions for tidal flushing of the site. It was determined that a minimum breach of 200 ft. would be required to allow full tidal fluctuations inside the dike and to reduce water velocities at the breach site.

During the design phase, Dr. Ron Thom of Battelle Marine Sciences Lab was consulted regarding several parameters of the project. He advised that more than one breach be used to assure adequate flushing to achieve the ecological objectives of the project. From his recommendations, additional modeling was done, and one 250-ft. and two 40-ft. breaches were selected.

To provide for public access and routine maintenance, each of these breaches will be bridged.

3) Dr. Thom's expertise was applied to the problem of eradicating reed canary grass and reestablishing a native intertidal plant community to the site. Although control of reed canary grass is poorly understood, certain controls are more effective for addressing the "rooted" growth type found on Spencer Island.

Recognizing that *Phalaris* is salt- and flooding-intolerant, Dr. Thom predicts that "restoration of tidal action along with the occasional penetration of saline waters (at 4.0 ppt) into the restored system should be effective in killing *Phalaris* over much of its present distribution." He also expects that removal of live and dead organic matter from the system, following breaching, will occur naturally over an extended period of time.

Observations of a 25-year-old naturally breached area on Mid Spencer, containing similar elevations and salinities, led Dr. Thom to predict that a more diverse native community of *Carex* and other emergent macrophytes are likely to recolonize southern Spencer naturally. Based on rates of plant community change in well studied sites like Salmon River in Oregon, Gog-Le-Hi-Te in Tacoma, and Elk River marsh in Grays Harbor, he expects that community adjustment will take place rapidly for roughly five years following the breach, and then more gradually for a period of at least 11 years.

In summary, his recommendations for aiding in the transition of the plant community were to breach the dike, monitor what happens naturally over the first couple of years, and take actions to influence the system (remove organic material, conduct a formal transplanting program, etc.) only if necessary.

4) Increasing habitat attributes for juvenile salmonids and other fish species focused on providing access to and from holding areas, for feeding and overwintering. Based on Washington Department of Fish and Wildlife estimates, approximately 6.5 million chinook, 3.5 million coho, and 5 million chum smolts pass through the estuary annually. On even years 32.5 million pink smolts can be added to these figures.

In the life cycle of the salmon, estuaries are critical to their transition from freshwater to saltwater environments. Following dike breaching brackish marsh development is anticipated, and it is this type of habitat that juvenile salmon access during high tide to forage and seek refuge. These low-current refuge areas prevent juveniles from being transported into marine environments prematurely, while reducing exposure to potential predators at a susceptible time in their life history. Following breaching, depressional areas and scour channels in southern Spencer will provide important refuge to fish during tidal cycles.

To address concerns of fish stranding in the northern portion of the island, connection of existing drainage channels was made, and blocked interior culverts were removed. Connecting interior ditches allows fish passage from the interior cross levee culverts, through existing drainage ditches in the north, back into Union and Steamboat sloughs. Excavated material from these activities was used to create about 30 small nesting islands throughout the northern portion.

5) Before dike breaching, baseline monitoring was conducted to provide a research base for comparing pre- and post-breach phases.

First, a vegetation community map was completed using National Wetlands Inventory information, aerial photo interpretation, and field reconnaissance.

Second, a point intercept field survey of plant species was completed to assess percentages of cover on the breach site. Six transects were established and point data gathered along 10-meter intervals throughout the emergent portion of the site.

Elevation data was gathered for the breach site using GPS equipment. A HEP analysis was conducted selecting red tail hawk, kingfisher, mallard, wood duck, great blue heron, and muskrat as models. Unfortunately salmon models were not available for application. Wetland functions of Spencer Island were assessed using WET. Functions expected to increase following the breach are nutrient removal, production export, and sediment/toxicant retention.

Some fish monitoring was conducted to characterize existing juvenile salmonid use of the island. Minnow and fixed channel traps were used to sample fish activity at existing culverts penetrating the exterior dike. Primary sticklebacks were found inside the island and all four species of salmon with sticklebacks on the outside.

Future monitoring tasks will include tide gauge and current velocity data gathering, aerial photo analysis, elevation surveys, water quality data, vegetation diversity and community structure, and waterfowl and fish surveys. Initial assessment protocols for monitoring have been developed by Ron Thom, with Dr. Charles Simenstad of the School of Fisheries at the University of Washington providing a database storage and analysis structure to access monitoring information collected on Spencer.

WETLAND RESTORATION STATUS

Construction of the cross levee was completed in early 1993. This was followed by completing the northern island tasks of replacing and removing culverts, connecting ditches, and creating nesting islands. The dike in the southern portion was breached in the early morning hours of Nov. 19, 1994, beginning the restoration experiment.

Current efforts include shifting the project into long-term post breach monitoring, initiating long-term reforestation, and providing public access and interpretive elements. In the meantime, a long-term watershed-based wetlands restoration program has been designed as the next phase of the Puget Sound Plan's Wetlands Restoration Program.

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PUGET SOUND

RESEARCH '95

SESSION 3B

ENVIRONMENTAL MEASUREMENT

Session Chair:

David Peeler
Washington Department of Ecology

USE OF EMPIRICAL BSAF IN THE DEVELOPMENT OF HUMAN HEALTH SEDIMENT CRITERIA FOR NONIONIC ORGANIC CHEMICALS

David E. McBride and F. Joan Hardy[1]

INTRODUCTION

Hydrophobic organic chemicals such as polychlorinated biphenyls (PCBs), dioxins and furans, DDT, and various aromatic hydrocarbons have been found in aquatic ecosystems. Their presence is primarily the result of human activities. These chemicals are of concern not only because of ecological impacts but also because of potential adverse effects to humans who ingest contaminated seafood.

Their strong affinity to organic components allows hydrophobic chemicals to accumulate within sediments, which serve as a chemical reservoir. Once in the sediments, contaminants may bioaccumulate in benthic organisms through direct contact with the sediments or through ingestion. Previous research and regulatory actions have prioritized the development of criteria designed to protect benthic populations. However, bioaccumulation of contaminants from sediments to benthic organisms and subsequent transfer through the food web provide an exposure pathway to higher trophic level organisms, including humans.

Several studies have demonstrated that sediments from industrialized bays and estuaries of Puget Sound are substantially contaminated by various inorganic and organic substances as a consequence of industrial pollution, non-point source pollution, and other human activities (Ginn and Pastorok, 1992; Malin et al., 1980, 1982). Bioaccumulation studies of organic compounds in Puget Sound have focused on urban embayments that are contaminated from multiple discharges. While several hundred organic compounds have been detected, only a few have been identified due to the lack of reference standards (Gahler et al., 1982). Nonionic organic compounds observed in Puget Sound sediments include PCBs, DDT and metabolites, chlorinated benzenes, and various aromatic hydrocarbons.

Epidemiological studies have documented human health effects and increased levels of organic chemicals in the blood of human populations consuming contaminated fish (Swan, 1988; Gossett et al., 1989). In addition, several studies have shown the relative importance of consumption of contaminated fish in contributing to elevated risks of cancer relative to other exposure pathways (Bro et al., 1987; Connor, 1984). From a regulatory perspective, the presence of nonionic organic compounds in both sediment and fish tissue from Puget Sound, combined with evidence of adverse health effects and elevated cancer risks, shows the need to assess potential risks to humans associated with contamination of aquatic organisms.

In the 1980s, the Washington Legislature mandated the development of sediment standards to protect ecological and human health under the state's Model Toxics Control Act (MTCA). The Washington Department of Ecology (Ecology) promulgated Sediment Management Standards (SMS) in early 1991 to set levels of contaminants to "reduce and ultimately eliminate adverse effects on biological resources and significant human health threats" resulting from contaminated sediments in marine, low-salinity, and fresh waters. Sediment quality standards for the protection of Puget Sound marine biological resources are the only criteria that have been adopted at this time.

The Washington Department of Health (DOH) has a cooperative agreement with Ecology to provide guidance in the development of sediment criteria protective of human health. These criteria will be used by Ecology to set dredged disposal concentrations, clean-up levels, and discharge permit concentrations. DOH has reviewed various options to address the potential accumulation and biomagnification of contaminants from sediment to aquatic organisms. The goal of this effort is to set sediment standards that will prevent contaminant concentrations in aquatic organisms from accumulating to levels that would pose a human health problem for those who consume seafood from Puget Sound.

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DEFINITIONS

Equilibrium partitioning (EqP): The distribution of a chemical between two different phases (commonly water and organic carbon) measured under equilibrium conditions.

Octanol/water partition coefficient (K_{ow}): The ratio, at equilibrium, of the concentration of a substance in the octanol phase to its concentration in the aqueous phase in a two-phase n-octanol/water system. The partition coefficient (log K_{ow}) is the log ratio of chemical concentrations in the two solvents at equilibrium. Octanol, a nonpolar molecule, is used as a surrogate for lipids (fat) or organic carbon.

Bioaccumulation: The net accumulation by an organism of a chemical from the combined exposure to water, food, and sediment.

Biomagnification: The process of bioconcentration and bioaccumulation by which tissue concentrations of bioaccumulated chemicals increase as the chemical passes through two or more trophic levels.

Bioconcentration factor (BCF): A laboratory-derived partition coefficient for the distribution of a chemical between water and an organism, where exposure is solely from water.

Bioaccumulation factor (BAF): A partition coefficient for the distribution of a chemical between water and an organism exposed through all routes including water, food, and contact with sediments.

Biota-to-sediment accumulation factor (BSAF): A partition coefficient for the distribution of a chemical between sediment and an organism. BSAF has been called the bioavailability index (BI), the accumulation factor (AF), and the biota-sediment factor (BSF).

Lipid and carbon normalization: Partitioning of nonionic organic compounds in fish tissue and water, or sediment and water, is highly correlated with either the lipid or organic carbon content, respectively. The greater the lipid or organic carbon content, the greater the capacity of the fish tissue or sediment to bind to nonionic organic compounds. In order to account for differences in either lipid or organic carbon concentrations, one should normalize the nonionic organic compound by either the amount of lipid in the fish tissue or organic carbon in the sediment to compare concentrations in different fish or different sites.

BACKGROUND

In developing human health sediment standards, DOH employed a two-tiered approach for Puget Sound. This approach allows for an initial set of criteria that saves time and expense for regulators and the regulated community while ensuring adequate protection for human health. The first tier is generic rather than specific in nature in that Tier I standards are developed for all of Puget Sound. Development of Tier I standards relies on existing sediment and fish tissue data as well as existing human health criteria, such as the U.S. Environmental Protection Agency's (EPA) cancer potency factors (CPF) for chemicals known or suspected to cause cancer and the reference dose (RfD) for noncarcinogens. Tier I sediment quality criteria are set at levels for the most sensitive endpoint of the population with greatest potential exposure. These criteria values are purposely conservative to ensure protection of those at greatest risk. However, Tier I criteria have a greater associated uncertainty than do Tier II criteria. From a regulatory perspective this is appropriate because the goal of developing Tier I standards is to identify sediment chemical concentrations that are clearly not of human health concern based on exposure through the consumption of seafood.

A second tier allows for a more accurate and thereby a more certain calculation of sediment standards based on site-, chemical-, and species-specific data. Because it requires collection of additional data, Tier II is more costly and time consuming than Tier I. The goal in developing Tier II standards is to identify with greater certainty chemical concentrations in sediments that are not of human health concern based on exposure through the consumption of seafood. The relationship of Tier I to Tier II is shown in a flow chart (Figure 1). For the remainder of this document, DOH discusses the development of Tier I sediment standards only.

Chemicals detected in a sediment sample are compared initially to a list of chemicals of concern (Figure 1). If none of the detected chemicals is found on the chemicals of concern list, no regulatory action is taken. If a detected chemical is on this list, the chemical concentration is compared to that of Puget Sound background reference areas. If the chemical concentration falls below an established background reference concentration, no further regulatory action will ensue. If the concentration is above background area reference concentrations, the next step is a comparison with Tier I human health sediment quality criteria (SQC) for that chemical. If the concentration is below the SQC, no regulatory action will ensue. However, if the concentration exceeds the SQC, one of two actions is taken. The first is a regulatory action such as site cleanup, limiting or confining disposal of dredged sediments, or the requirement of an effluent discharge permit. A second possible action is a Tier II analysis requiring site-specific data to derive sediment criteria.

In the effort to develop criteria, DOH derived a list of chemicals that are of concern from a human health perspective and for which criteria would be adopted into the sediment management standards (SMS). This list of chemicals is referred to as "chemicals of concern" and was developed based on several factors. These factors include known sources of the chemical in Puget Sound, whether a chemical is present in either Puget Sound sediments or fish, whether a chemical has the potential to bioaccumulate in aquatic organisms, and the chemical's potential toxicity to humans.

As displayed in a flow chart, background area concentrations are used to compare sediment concentrations (Figure 1). Background area reference standards have been established from areas in Puget Sound that are free from direct anthropogenic activities. Reference standards were calculated based on detected chemicals found at these locations. It is possible to have background area reference standards that are above human health sediment criteria. This situation would indicate that pollution is ubiquitous or that chemical concentrations are high due to natural causes. It is not feasible to clean up sites below background area concentrations, although it is recognized that there may be a human health concern associated with these concentrations. This scenario will be addressed by way of a DOH health advisory.

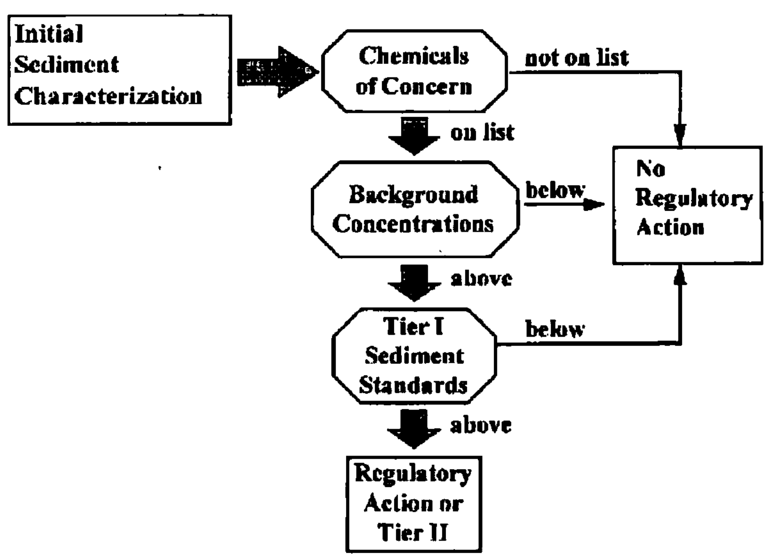

Figure 1.

In deriving Tier I sediment quality criteria (SQC), DOH used a water quality criteria standard risk assessment formula modified for both carcinogen and noncarcinogen sediment criteria.
For carcinogens:

$$SQC=\frac{RxBWxATxUCF}{CPFxBSAFxIFxED} \tag{1}$$

For noncarcinogens:

$$SQC=\frac{RfDxBWxATxUCF}{BSAFxIFxED} \tag{2}$$

where:

SQC is the sediment quality criteria below which no adverse human health effect is expected, replacing a water quality criteria (WQC). SQC is in units of µg of chemical/kg organic carbon. R is the target risk level, usually set at one in one million. BW is the average body weight (kg) of an adult. AT is averaging time, the period over which exposure occurs (75 years for an average life span). CPF is the chemical-specific cancer potency factor (mg of chemical/kg of body weight per day)$^{-1}$ for those chemicals known to cause cancer. RfD is the chemical-specific reference dose (mg of chemical/kg of body weight per day) for noncarcinogens. BSAF is DOH's empirically derived biota-to-sediment accumulation factor (kg organic carbon/kg lipid), which is used in place of a EPA's water quality BCF value. IF is the ingestion frequency of an organism normalized to lipid concentration (g lipid/day). Based on a review of consumption surveys, DOH chose a point value of 96.1 g/day, which represents the median value of several 95 percentiles from four Puget Sound consumption surveys (EPA, 1988). This value is normalized to the lipid concentration of English sole, a target species chosen for this process. Lipid concentrations for English sole are approximately <1 percent - 2 percent. ED is the exposure duration in years, here set at 30 years. Finally, UCF is the unit conversion factor ((µg chemical/mg chemical * kg organic carbon/g organic carbon)/1*10^{6}).

DERIVING DRAFT EMPIRICAL BSAF VALUES FOR TIER I / RESULTS

The following section describes the development of empirically derived BSAF values by DOH. First, literature searches were conducted for published BSAF values. Next, several large databases were identified in peer-reviewed and gray literature, including BSAF values from Parkerton (1991), COBIAA (1992), and EPA's Great Lakes Water Quality Initiative (1994). In total, more than 6,000 individual BSAF data points were obtained. These data represent a variety of chemicals as well as aquatic species found in various habitats. Once collated, a combined database was organized to allow the user to query for a variety of parameters including chemical, species, and chemical log K_{ow}.

From this collated database, DOH searched for BSAF values representing upper trophic level fish species. More than 1,200 data points were identified for fishes occupying several trophic levels. From this list, chemicals and their corresponding BSAF values were grouped by log K_{ow} values. BSAF values were then arranged in half log K_{ow} increments. Chemicals with log K_{ow} values less than four were grouped due to limited data and lower bioaccumulation potential. Similarly, chemicals with log K_{ow} values greater than eight were grouped.

Once additional data become available, DOH may group chemicals into distinct classes that share similar chemical properties. This would increase the accuracy of BSAF values because categorization would be based on both chemical class and log K_{ow} values. Currently, data are limited to categorization by K_{ow}. However, DOH recommends that future work focus on grouping by both chemical class and K_{ow}.

Descriptive statistics were calculated for BSAF values in each K_{ow} range. Draft mean, median, and the 75 percentile value are shown graphically (Figure 2).

Once empirical BSAF values have been categorized by log K_{ow}, a BSAF value may be chosen for any given nonionic organic chemical with a known log K_{ow} by matching that chemical's log K_{ow} to the range

of log K_{ow}'s from the empirical data. The assigned BSAF serves as a surrogate for that chemical or any other nonionic organic chemical having a log K_{ow} within that range.

Surrogate BSAF values for a given chemical along with its CPF or RfD value are then substituted into equations 1 and 2 to calculate sediment quality criteria for carcinogens or non-carcinogens. Surrogate BSAF values were derived for five nonionic organic chemicals (hexachlorobutadiene, pentachlorophenol, p,p'-DDT, PCB-1260, and 2,3,7,8-TCDD) found in Puget Sound sediments. These surrogate BSAF values, combined with a chemical-specific CPF, were used to calculate draft chemical-specific human health sediment quality criteria using equation 1 (Table 1).

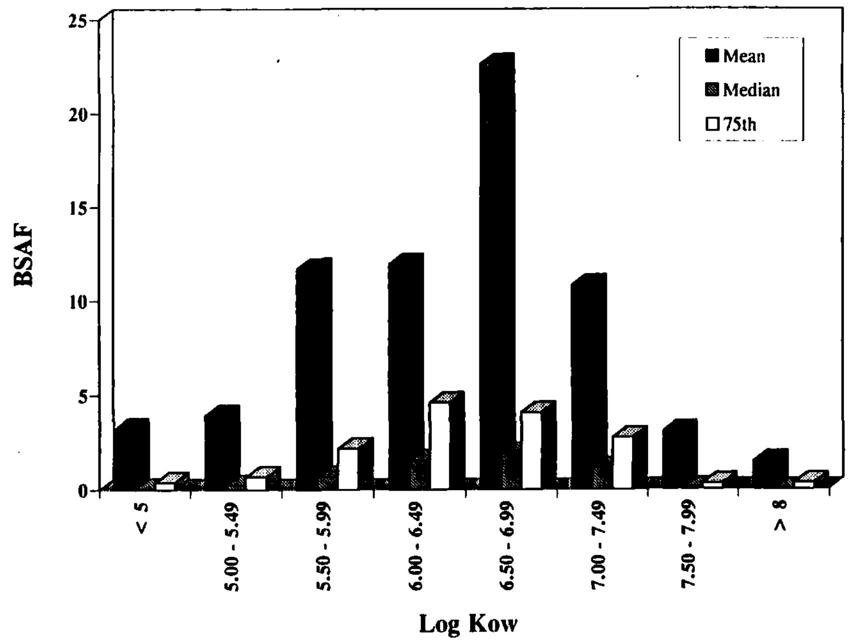

Figure 2. Empirical BSAF vs. log K_{ow}

Table 1. Comparison of draft human health sediment quality criteria (SQC) with current sediment management standards (SMS) and Puget Sound Urban Bay sediment concentrations

	HCBD	PCP	DDT	PCB	Dioxin
SQC (Draft)	20,221	1,877	295	5.1	0.0003
Current SMS	3,900	360,000	NA	12,000	NA
Range*	ND - 34,600	ND - 484,600	ND - 24,600	ND - 141,670	ND - 54,580
Median*	859	862	135	1,120	14,580
Det. Freq.*	4.5%	6.5%	9.4%	41.8%	100%
	n=1431	n=1470	n=1267	n=739	n=8

units: ug chemical/kg organic carbon
HCBD = hexachlorabutadiene
PCP = pentachlorophenol
DDT = p,p'-DDT
ND = nondetected
PCB = PCB-1260
Dioxin
Dioxin = 2,3,7,8-TCDD

DISCUSSION

The aim of developing Tier I human health sediment criteria values is to identify sediment chemical concentrations that are clearly not of human health concern based on exposure through the consumption of seafood and to identify those sediments that are of potential concern. The use of surrogate BSAF values

coupled with an EPA modified risk equation will allow regulators to meet these goals. Such human health-based sediment standards could be used to set clean-up levels that would protect against further bioaccumulation and biomagnification of contaminants from sediments to aquatic organisms, to evaluate dredging material for its potential to bioaccumulate in aquatic organisms, and to prevent sediments from becoming contaminated from industrial discharges.

There are several advantages in using empirical BSAF values in setting human health-based sediment standards. First, the use of empirical BSAF values is a logical and uncomplicated method of assessing bioaccumulation and biomagnification of contaminants from sediments to aquatic organisms. Furthermore, BSAF values may be derived for a variety of nonionic organic chemicals with known K_{ow} values for Puget Sound. Since empirical BSAF-derived sediment criteria rely on existing data, they are a cost- and time-effective method of evaluating sediments.

Limitations of this method must also be recognized. One limitation is that surrogate BSAF values are not based on chemical and species data from specific sites. Furthermore, surrogate BSAF values may overestimate the bioaccumulation and biomagnification for chemicals that are metabolized, thereby reducing net bioaccumulation. Finally, relating fish tissue concentrations to sediment concentrations using empirical BSAF values could overestimate sediment bioavailability of that chemical if water column routes of exposure are significant.

Human health-based sediment quality criteria may be calculated for either fish or shellfish, depending on which type of organism poses the greatest health threat. This flexibility is useful in identifying chemicals that are metabolized by some organisms but not by others. If not metabolized, the chemical would bioaccumulate in the organism, which then would become a potential health threat if consumed. A simple comparison of a criterion based on fish with a criterion based on shellfish would indicate which resulting sediment concentration would be more restrictive. The more restrictive criterion would be used to set a standard for that chemical.

The use of the modified risk equation would allow both the regulator and the regulated community flexibility in implementation. Such flexibility could be achieved by using several risk levels for different levels of cleanup or dilutional zones. Furthermore, average sediment concentrations may be used in areas rather than relying on single "hits" of a chemical. In this case, averaging would result in more realistic levels for cleanup than would use of a single high or low chemical "hit."

DOH is advocating the use of the 75 percentile value to serve as a surrogate for chemicals within a chemical class for a given log K_{ow}. The 75 percentile was chosen for several reasons. Mean BSAF values are likely to be influenced by outliers in the data. The further the outlier is from the mean, the greater its effect. Using the median value avoids problems with outliers but does not account for half of the BSAF values that are greater than the median. Consequently, the use of a percentile value was chosen to avoid problems with outliers and to ensure that this surrogate would be protective by accounting for most of the data. The use of higher percentile values (90 or 95) was discounted because of the existence of outliers that would result in over-protective criteria.

Current sediment management standards (SMS) for the protection of aquatic organisms are listed for comparison with human health sediment quality criteria (Table 1). Of the five chemicals shown, all but hexachlorobutadiene result in more restrictive sediment standard based on human health rather than on protection of aquatic organisms. Currently there are no SMS for DDT or dioxin.

In addition, draft sediment quality criteria values for these five chemicals were compared with known concentrations in Puget Sound urban embayments. Organic carbon-normalized sediment data from Elliott Bay, Everett Bay, Bellingham Bay, Dyes Inlet, Commencement Bay, and Budd Inlet are shown (Table 1). Although the upper range of the data for each chemical is well above draft human health sediment quality criteria values, median values for hexachlorobutadiene, pentachlorophenol, and p,p'-DDT fall below draft human health sediment quality criteria. PCB and dioxin median values from Puget Sound urban embayments were several orders of magnitude higher than the draft human health SQC for those chemicals. From a regulatory standpoint, remedial decisions involving carcinogenic compounds are likely to be based largely on human health rather than ecological concerns.

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MEASURING PLANAR CHLOROBIPHENYL CONGENERS IN PUGET SOUND MARINE BIOTA BY HPLC/PDA

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INTRODUCTION

Chlorobiphenyls (CBs) are a complex mixture of 209 possible congeners that are widespread and persistent environmental contaminants. These congeners are numbered for simplicity (e.g., 3,3',4,4'-tetrachlorobiphenyl is numbered CB 77), with the more highly chlorinated CBs having higher congener numbers. In aquatic animals, accumulation of CBs is determined not only by the concentrations and availability of these compounds in the surrounding environment, but also by physiological processes (e.g., metabolism, depuration) in the organisms (Barron, 1990). The most toxic CBs are isosteres of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) that show TCDD-like toxicity. The toxicity of TCDD is mediated through a specific cellular receptor, known as the Ah receptor (Safe, 1990). The Ah receptor is involved in the regulation of genes for several proteins. These dioxin-like congeners include non-*ortho* substituted CBs and certain mono-*ortho* and di-*ortho* substituted analogs (Ahlborg et al., 1994). Although the dioxin-like CB congeners are only 0.00001 to 0.1 times as toxic as TCDD (Ahlborg et al., 1994), these congeners are often found in much higher concentrations in the marine environment than are the polychlorinated dibenzodioxins (PCDDs) or dibenzofurans (PCDFs). Thus, the dioxin-like CB congeners may contribute substantially to the body burden in marine organisms of compounds with physical properties similar to TCDD (de Boer et al., 1993; Petreas et al., 1992; Smith et al., 1990).

Monitoring for toxic chemical contaminants, such as CBs, in commercially and recreationally important seafood species is necessary to evaluate the potential risks to human health. The U.S. Food and Drug Administration (FDA) has set its action level for CBs (based on total CBs) in seafood at 2 μg/g, wet weight (2 ppm). Total CB concentrations may not accurately reflect the actual toxic potency of the CB mixtures in seafood samples because the dioxin-like congeners are believed to contribute the majority of the toxic response of environmental CB mixtures. In order to estimate the relative toxicities of dioxin-like CBs in seafood tissues, TCDD toxic equivalents (TEQs) are currently being determined using congener-specific toxic equivalency factors (TEFs) and concentrations of dioxin-like CBs (Safe, 1990; Ahlborg et al., 1994). Although the FDA has set no regulatory levels for TCDD or TEQs for dioxin-like compounds (e.g., PCDDs, PCDFs, CBs), Health and Welfare Canada has set a TCDD action level of 20 pg /g, wet weight (Ahmed, 1991). In recent studies, the Canadian TCDD regulatory levels have been used to evaluate TEQs of dioxin-like compounds in various foods (Birmingham et al., 1989; de Boer et al., 1993).

We have recently developed a relatively rapid method that uses high performance liquid chromatography (HPLC) coupled with photodiode array (PDA) detection (Krahn et al., 1994) to measure selected CBs and DDTs in tissues of marine species. Using this analytical technique, concentrations of dioxin-like CBs and other selected CBs were determined in three seafood species collected from Puget Sound sites (Ylitalo et al., 1995). From this initial data, total CB concentrations and TEQ concentrations of dioxin-like CBs were calculated and compared to the appropriate regulatory limit (e.g., FDA, Canadian). These preliminary results showed that the mean total CB concentrations in the edible seafood tissues fell below the FDA regulatory limit and that TEQ concentrations of dioxin-like CBs measured in these tissue samples did not exceed the Health and Welfare Canada TCDD regulatory limit.

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METHODS AND MATERIALS

Sample Collection

English sole (*Pleuronectes vetulus*) and Dungeness crab (*Cancer magister*) were captured by otter trawl at two urban sites (Elliott Bay and Commencement Bay) and one non-urban site (Useless Bay) in Puget Sound, Wash. (Figure 1), as part of NMFS's Seafood Product Quality & Safety (PQ&S) Program. Blue mussels (*Mytilus edulis*) were obtained from rocks near the three recreational fishing sites. The edible tissues of these seafood species (fish muscle, crab claw muscle and hepatopancreas, and the whole body of blue mussel) were collected (n=10 samples per site) and stored at -20°C until analysis.

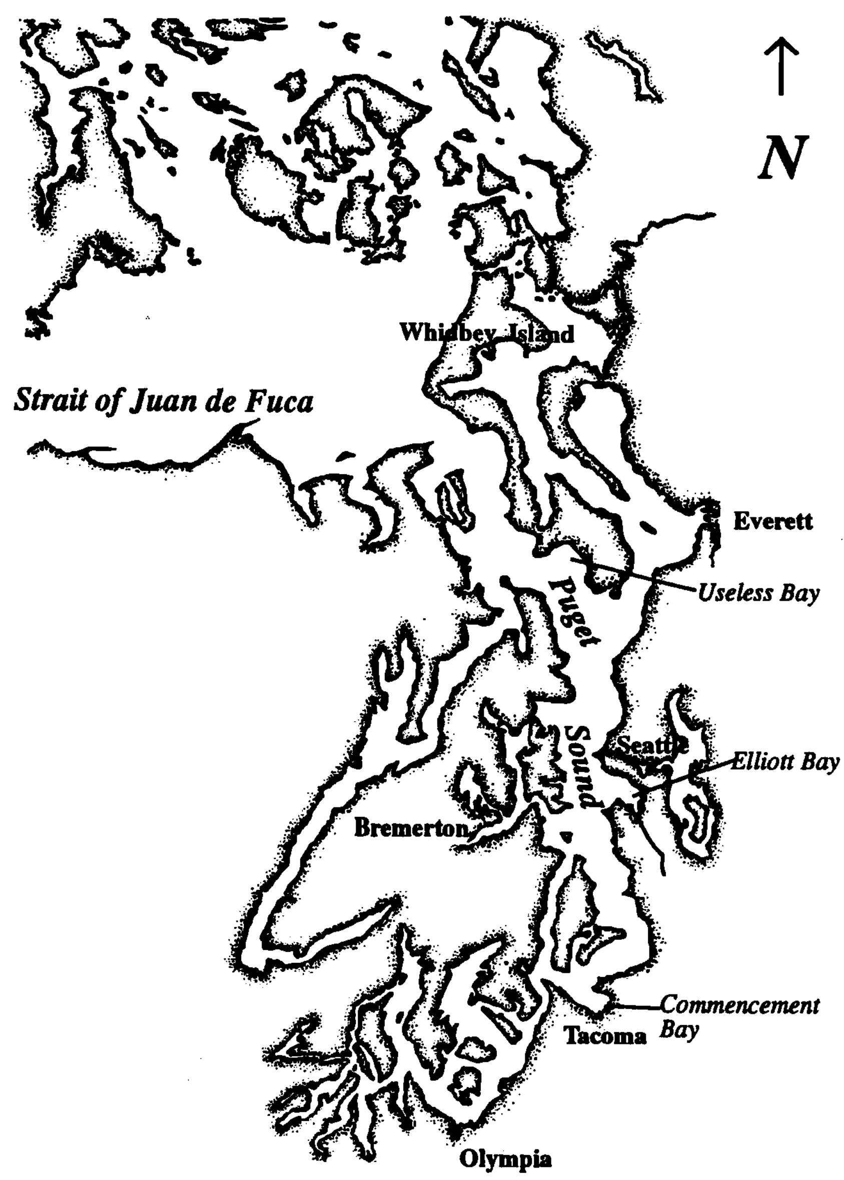

Figure 1. Locations of Puget Sound sites where blue mussel, Dungeness crab and English sole samples were collected (Commencement Bay, Elliott Bay and Useless Bay)

Sample Extraction and Cleanup

Edible seafood tissues were analyzed for CBs using the extraction and cleanup method of Krahn et al. (1994). Briefly, 2.0 - 4.0 g edible tissue, 20-mL hexane/pentane (1:1 v/v), 5 g sodium sulfate and the surrogate standard (1,7,8-TriCDD; 250 ng) were homogenized and centrifuged, and the extract was decanted into a concentrator tube. The extraction process was repeated, and the extracts were combined and evaporated to ~1 mL.

The sample extract was loaded onto a gravity-flow cleanup column that contained a glass wool plug, silica gel, basic silica gel and acidic silica gel to remove lipids and other interfering compounds. The CBs were eluted from the cleanup column with 14 mL hexane/methylene chloride (1:1 v/v) and collected into a concentrator tube. The HPLC internal standard was added to each sample (1,2,3,4-TCDD; 250 ng), and the solvent volume was reduced to ~150 μL.

HPLC/PDA Analyses

Eleven dioxin-like CB congeners (CBs 77, 81, 105, 118, 126, 156, 157, 169, 170, 180 and 189) were resolved from other selected CBs (CBs 101, 128, 138 and 153) and chlorinated pesticides (e.g., DDTs, hexachlorobenzene) by HPLC on 2(1-pyrenyl) ethyldimethylsilylated silica (PYE) analytical columns cooled to 9°C and were monitored with a PDA detector (Krahn et al., 1994). The chlorinated hydrocarbons were identified by comparing their UV spectra (200-310 nm) and retention times to those of reference standards in a library. Analyte purity was confirmed by comparing UV spectra collected for a peak to the apex spectrum.

Calculation of Total CBs

Using the areas and concentrations determined from the HPLC/PDA chromatograms, the total CB concentrations were calculated using the following formula: ΣCBs = ΣCB concentrations + Σ unidentified peak concentrations (estimated based on response of CB 101). The CB 101 response was the closest in value to the mean response factor of all 15 CBs measured in this study.

Calculation of Total TEQs

Eleven dioxin-like CB congeners (CBs 77, 81, 105, 118, 126, 156, 157, 169, 170, 180 and 189) were quantitated, and the CB toxic equivalents (TEQs) were calculated according to the method of Ahlborg et al. (1994) using an additive model of toxicity for dioxin-like CB congeners. In this method, molar concentrations of individual CB congeners were multiplied by their toxic equivalency factors (TEFs) recently recommended by World Health Organization-European Centre for Environment and Health (WHO-ECEH) and the International Programme on Chemical Safety (IPCS) (Ahlborg et al., 1994).

Statistical Analysis of Data

Total CB and total CB TEQ data were analyzed using one-way analysis of variance (ANOVA). To determine if significant site differences existed within a seafood tissue, the total CB and total CB TEQ data were analyzed using Fisher's Least Significant Difference test (two-tailed) at a 0.05 probability level.

RESULTS AND DISCUSSION

In seafood samples analyzed, the most abundant CBs were the higher chlorinated congeners (Figure 2). Congeners, such as CBs 153 and 138, are major components of certain CB technical mixtures (Duinker et al., 1988; Schulz et al., 1989) and have been frequently detected in high concentrations in a wide range of marine biota (Loizeau and Abarnou, 1994; McFarland and Clarke, 1989; Porte and Albaiges, 1993). Of the 11 dioxin-like CBs we measured in these seafood samples, CB 118 was the only one found in all tissues, except in blue mussels from Useless Bay, our reference site. Furthermore, we measured certain non-*ortho* substituted congeners only in samples of crab hepatopancreas from Elliott Bay (CBs 77 and 126) and Commencement Bay (CB 77). Consistent with our results, the dioxin-like CBs have recently been reported in tissues from a wide variety of marine biota, with the mono-*ortho* substituted planar CBs (e.g., CBs 118

and 105) being the predominant dioxin-like CBs detected (de Boer et al., 1993; Hong et al., 1992; Jarnberg et al., 1993; Sericano et al., 1994). In these studies, non-*ortho* substituted CBs (e.g., CBs 77, 126 and 169) were found in many of the tissue samples, with concentrations ranging from a few pg/g to several ng/g.

Significantly higher total CB concentrations (Figure 2) and CB TEQ concentrations (Figure 3) were found in English sole muscle, Dungeness crab muscle and hepatopancreas from Elliott Bay compared to the same species sampled from either Commencement Bay or Useless Bay, the reference site. In contrast, a previous study showed higher total CB concentrations in English sole muscle from Commencement Bay than in English sole muscle from Elliott Bay (Landolt et al., 1985). These differences in rank order of sites may have resulted because fish collected in the Landolt study (1985) were caught at various locations (e.g., several piers) within a general site, whereas the English sole collected for our study were captured by trawl in Commencement Bay. A previous study (Stein et al., 1992) has shown that concentrations of CBs in liver of rock sole from Commencement Bay were substantially less than the CB concentrations in liver of English sole from a waterway (Hylebos) of Commencement Bay. We also found that the concentrations of total CB and TEQ concentrations of CBs were significantly higher for blue mussels from both Elliott Bay and Commencement Bay than for blue mussels from the Useless Bay reference site; however, there was no significant difference in concentrations between Elliott Bay and Commencement Bay.

The Puget Sound seafood tissues we analyzed in this preliminary study contained total CB concentrations that fell below the FDA action level (2 μg/g, wet weight), except for hepatopancreas samples of Dungeness crab from Elliott Bay. Similarly, in a previous Puget Sound study, all the fish tissues analyzed contained total CB concentrations that fell below the FDA action level (Landolt et al., 1987). As another estimate of human risk, we compared total TEQ concentrations in these tissues to the Health and Welfare Canda TCDD action limit (Table 2). Most of our samples had low dioxin-like CB TEQs; however, some samples of crab hepatopancreas from Elliott Bay and Commencement Bay that contained CB TEQs higher than the Health and Welfare Canada TCDD action limit. Frequent consumption of seafood that contain high concentrations of dioxin-like CBs may present a health risk (Williams et al., 1992).

Table 1. Mean total CB concentrations (μg/g, wet weight) in edible tissues of seafood from Puget Sound, Wash. The bold number indicates the mean total CB level that exceeded the FDA action level (2.0 μg/g, wet weight). Modified from Ylitalo et al. (1995).

Site	Dungeness crab hepatopancreas	Blue mussel whole body	English sole muscle	Dungeness crab muscle
Elliot Bay (n=10)	**8.8**	0.12	0.32	0.12
Commencement Bay (n=10)	1.8	0.11	0.02	0.04
Useless Bay (n=10)	0.34	0.00	0.01	0.01

CONCLUSIONS

Although the non-planar CBs were the major congeners in our Puget Sound samples, several mono-*ortho* and non-*ortho* substituted congeners were found in the tissue samples analyzed. We found that the Elliott Bay samples had the highest total CB concentrations and TEQ concentrations of CBs compared to the tissues from other sites. At all sites, Dungeness crab hepatopancreas contained higher total CB concentrations and TEQs of dioxin-like CB compared to the other tissues. All the seafood tissues commonly consumed (crab muscle, whole mussels and fish muscle) contained total CB concentrations below the FDA action level. Dungeness crab hepatopancreas samples from Elliott and Commencement bays were the only tissues that had total CBs that exceeded the FDA action level and total CB TEQ concentrations that exceeded the TCDD Canadian regulatory limit.

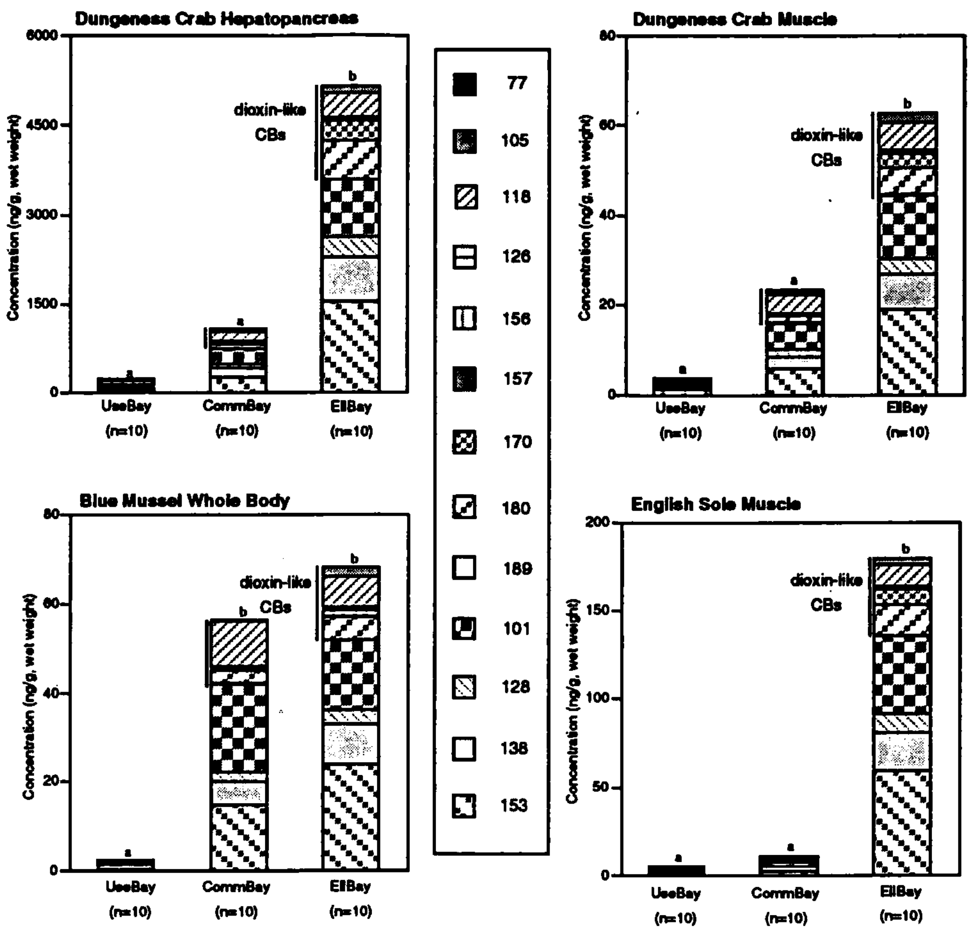

Figure 2. Relative concentrations of CB congeners (ng/g, wet weight) in various seafood tissues from three Puget Sound sites. Bars with unlike letters differ significantly; Fisher's Least Significant Difference test, $p < 0.05$. Data adapted from Ylitalo et al. (1995).

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Table 2. Mean total TEQs (pg TCDD/g, wet weight) in edible tissues of seafood from Puget Sound, Wash. The bold numbers are the mean total TEQs that exceeded the Health and Welfare Canada action level (20 pg TCDD/g, wet weight). Modified from Ylitalo et al. (1995).

Site	Dungeness crab hepatopancreas	Blue mussel whole body	English sole muscle	Dungeness crab muscle
Elliot Bay (n=10)	**140**	1.2	3.2	1.3
Commencement Bay (n=10)	**30**	1.0	.021	0.59
Useless Bay (n=10)	7.4	0.05	0.09	0.06

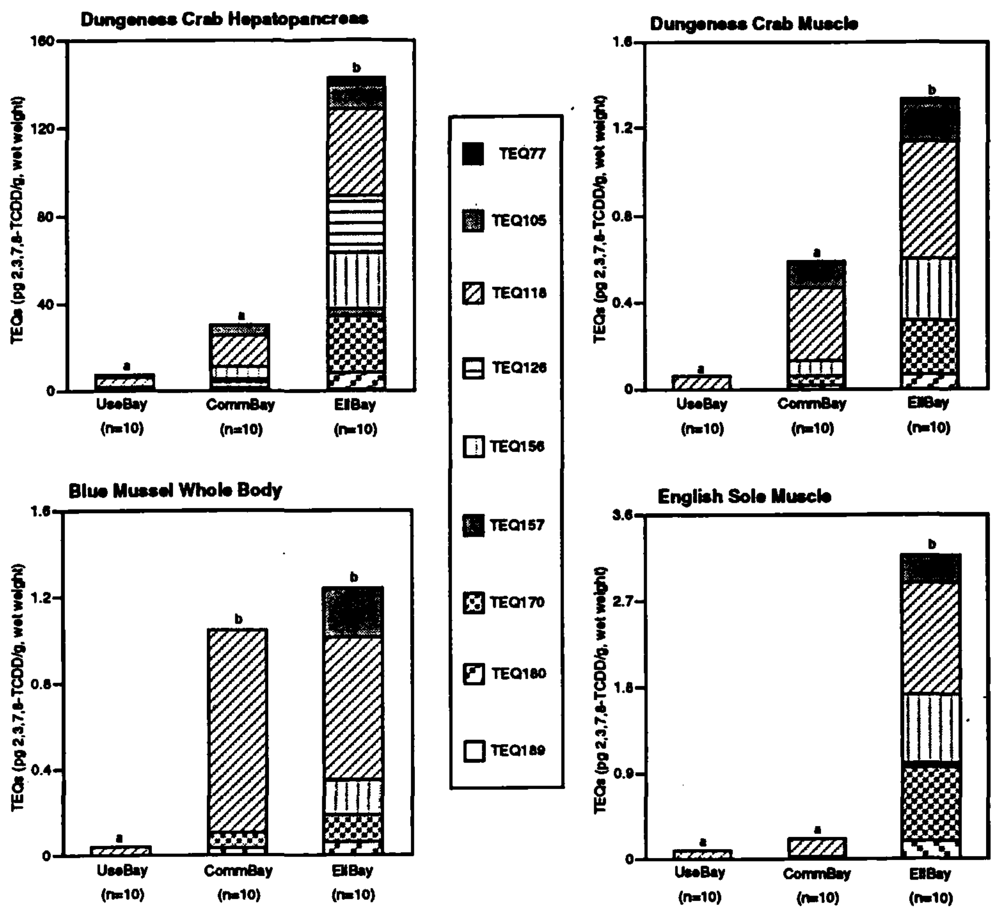

Figure 3. Toxic equivalents (pg TCDD/g , wet weight) calculated from dioxin-like CBs in various seafood tissues from three Puget Sound sites. Bars with unlike letters differ significantly; Fisher's Least Significant Difference test, p < 0.05. Adapted from Ylitalo et al. (1995).

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USE OF SEMIPERMEABLE MEMBRANE DEVICES TO MONITOR PAHs AND PCBs IN ELLIOTT BAY, SEATTLE, WASHINGTON

L.F. Lefkovitz and E.A. Crecelius[1]

BACKGROUND

Persistent hydrophobic organic compounds (HOCs), such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), enter the global aquatic environment from many sources. It is unlikely that inputs of HOCs such as PAHs will be greatly reduced in the upcoming decades if we continue to rely on petroleum-based fuels. PCBs, in contrast, have been banned for decades in this country from manufacture and use; however, elevated levels are still found associated with industrial sites where historical PCB contamination occurred. Monitoring water levels for these HOCs is difficult, due to the low solubility and subsequent low concentrations of the contaminants in the water column. In addition, the levels of HOCs in the water column could be somewhat variable over time, due to temperatures, tides, and other factors. Because of the hydrophobic nature of these compounds, they tend to bioaccumulate in aquatic organisms. Even when the water levels are low, there is a potential for bioaccumulation in aquatic organisms, such as fish and bivalves, to levels that could pose a human health risk.

Predicting bioaccumulation of persistent toxic organic chemicals using bivalves or fish either in a controlled laboratory setting or in the field is standard practice. The tests, however, are labor-intensive, and the chemical analysis of the resulting tissue samples is quite costly. In addition, it is difficult to interpret the results from these bioaccumulation tests, since the organisms accumulate the HOCs both passively, by partitioning from the water to their lipids, and actively, by ingesting particles that contain the HOCs. In addition, metabolization by the organisms could affect the concentrations.

A new device using a semipermeable membrane filled with a small amount of synthetic fish lipid (triolein) appears to simulate bioconcentration of HOCs. It also appears that using polyethylene alone could be a good predictor of bioaccumulation. The advantages of using the semipermeable membrane devices (SPMDs), with or without lipid, are numerous. They give the advantage of allowing a time-integrated sample; they can sample large volumes of water, allowing detection of relatively low HOC concentrations in water; and chemical analyses of SPMDs, especially those consisting of polyethylene alone, are simple and relatively inexpensive.

The SPMD including lipid was used successfully in a number of studies to estimate uptake by bivalves and other organisms as well as to attempt to predict "dissolved" concentrations of HOCs in water. SPMDs were deployed and favorably compared to concurrent caged-bivalve studies and to two other studies, one in the San Joaquin River (Prest et al., 1992), and the other in two bays in Massachusetts (C.S. Peven, F.J. Querzoli, and A.D. Uhler, unpublished data). SPMDs were also found to predict concentrations in fish in controlled pond enclosures (Huckins et al., 1990) and to estimate PAH concentrations in the water in the same enclosures (Lebo et al., 1992).

The theory and rationale for the use of these devices have been described in detail by Huckins et al. (1993). Briefly, the SPMD consists of the use of thin-walled, layflat polyethylene tubing filled with a thin film of a large-molecular-mass, neutral lipid, such as triolein. Even though material such as polyethylene is considered nonporous or dense, it contains transient cavities with diameters up to about 10 Å. This approaches the cross-sectional diameter of many environmental contaminants. Because of this size limitation, it is unlikely that analytes associated with aqueous particulates and dissolved organic carbon are able to access the SMPD lipid, resulting in a more realistic "dissolved" concentration. For a wide variety of organic compounds, a close correlation exists between the equilibrium triolein-water partition coefficients and the respective equilibrium octanol-water partition coefficients.

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USING SPMDs TO PREDICT WATER CONCENTRATIONS

Recent studies performed by Huckins et al. (1994) have provided sampling rates of a standard SPMD for a number of HOCs, and standard SPMDs have been shown to sample up to 9 L/day. Water concentrations can be calculated in two ways, as follows: 1) If the time of sampling corresponds to the linear uptake rate of the compound of interest, the concentration in the water to which the SPMD was exposed can be calculated using the uptake rates provided by Huckins et al. (1994); 2) if the SPMD has reached equilibrium with the water, the concentration in water can be approximated using the K_{ow} of the compound, as follows:

$$K_{ow} = [SPMD]/Cw$$

where [SPMD] is the concentration of analyte in the SPMD (nanograms per gram, ng/g); and Cw is the water concentration in nanograms per milliliter (ng/ml), or parts per billion (ppb).

When using polyethylene alone, the partition coefficient between polyethylene alone and water (K_{poly}) must be used. This K_{poly} is defined as

$$K_{poly} = [Polyethylene]/Cw$$

where [Polyethylene] is the concentration of the analyte associated with the polyethylene (nanograms per gram of polyethylene).

The advantage to using polyethylene alone is that it takes less time to come to equilibrium with most analytes, compared with the SPMD with lipid. Some compounds, such as the high-molecular-weight PAHs, do not come to equilibrium with the SPMD for two to three months. It is not practical to leave SPMDs in the environment for this length of time, due primarily to biofouling, which generally consists of heavy algal growth on the polyethylene, which interferes with uptake of the HOCs. Studies in our lab have shown that phenanthrene comes to an apparent steady-state (~90 percent equilibrium) between water and polyethylene within 4 days. This was repeated for two thicknesses of polyethylene (2 mil and 4 mil). In these studies, the $\log K_{poly}$ for phenanthrene was calculated to be 4.05. We are currently in the process of determining K_{poly} for a total of 16 PAH compounds and approximately 20 PCB congeners.

METHODS

SPMDs were deployed at 17 locations around Elliott Bay in the Duwamish River. Figure 1 shows the deployment sites. The sites were selected to cover a range of potential contamination levels and sources. The deployment consisted of a sheet of polyethylene (poly sheet) of dimensions 30 cm by 78 cm and a thickness of 4 mil. Each polyethylene sheet weighed approximately 19.5 g. These devices were suspended by a float approximately 1 m below the surface of the water and anchored to the bottom using a cement block. At one location, EB-14, two SPMDs were deployed at different depths, one at approximately 5 m, and one at about 1 m below the surface. The setups were left in place for two weeks. All were retrieved, with the exception of sites EB-3 (east of Duwamish Head), EB-7 (Duwamish turning basin), and the duplicate set adjacent to the ferry terminal (EB-15).

Samples were kept cold until their return to the laboratory, where they were frozen (-20°C). Prior to extraction, poly sheets were carefully wiped clean of biofouling, using deionized water and Kim Wipes. Poly sheets were then placed in cleaned, 8-oz. glass jars, filled with 200 ml of hexane and sealed with Teflon-lined lids. Samples were allowed to sit for a minimum of 48 hours in the hexane. The poly sheets were then removed, and a portion of the extract was reduced and cleaned using an Al/Si chromatography column. Extracts were then split, and a portion was analyzed for PAHs by gas chromatography/mass spectrometry (GC/MS) in the selected ion mode (SIM). The remaining fraction was further cleaned using high-performance liquid chromatography (HPLC) and analyzed for selected PCB congeners by capillary column gas chromatography/electron capture detection (GC/ECD).

RESULTS AND DISCUSSION

The objectives of this study were 1) to measure levels of HOCs around Elliot Bay using SPMDs, 2) to compare the distribution of the HOCs around Elliot Bay, and 3) to estimate water concentrations based on the levels observed in the SPMDs. We succeeded in obtaining measurable levels of PAHs and PCB congeners in all of the SPMDs retrieved.

All 16 PAHs were detected in one or more of the poly sheets collected from Elliott Bay. Table 1 lists the PAH concentrations as nanograms per poly sheet. Highest concentrations were found near Kellog Island in the Duwamish River. In general, the levels of PAHs increased down the Duwamish toward Elliott Bay, and decreased as the river empties into the bay. Levels at Duwamish Head (EB-1 and EB-2) in outer Elliott Bay were roughly 15 to 20 times lower than those in the Duwamish River and roughly 10 times lower than those along the eastern portion of Elliott Bay. Concentrations appeared to decrease near Magnolia Bluff, but were still elevated compared with those found near Duwamish Head.

Table 2 lists the concentrations of selected PCB congeners detected in SPMDS as nanograms of PCB congener per poly sheet. In Elliott Bay, virtually no PCBs were detected in SPMDs deployed west of Duwamish Head (<2 ng/poly sheet); however, levels began to increase near the West Waterway. Levels in Elliott Bay also increase from north to south counterclockwise around the shore to the vicinity of Pier 91, at which point they began to decrease. PCB concentrations also were elevated in the Duwamish River and were highest in the region between Harbor Island and the turning basin, with the highest levels near the 14th Avenue bridge. Overall, levels were about five times higher in SPMDs deployed in the river than they were in Elliott Bay. The pattern of PCB congeners observed was very similar in all samples collected in the Duwamish River.

The trend toward increasing concentrations around Elliott Bay counterclockwise from the mouth of the Duwamish River is well documented (NOAA, 1987). Studies of particulate and associated trace metal contamination show that movement

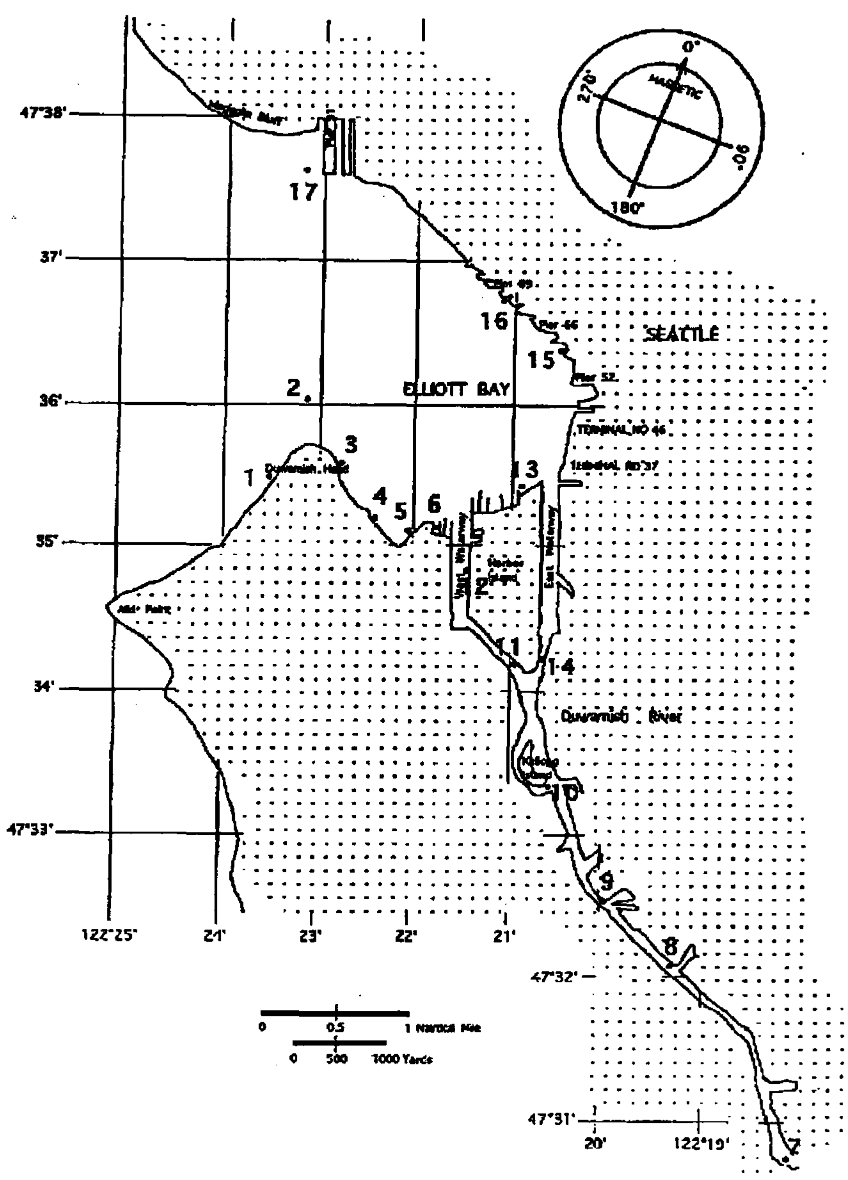

Figure 1. Elliot Bay and Duwamish River deployment sites

Table 1. Concentrations of PAHs in Polyethylene Sheets in Elliott Bay

	(Concentration ng/polysheet)															
PAHs	Solvent Blank	Field Blank	EB-1	EB-2	EB-4	EB-5	EB -6	EB-8	EB-9	EB-10	EB-11	EB-12	EB-13	EB-14	EB-14B	EB-16	EB-17
NAPHTHALENE	23	ND(a)	109	144	347	487	683	283	357	410	493	689	344	462	308	606	1004
ACENAPHTHYLE	ND	17	53	58	23	ND	ND	18	ND	ND	191	164	124	146	19	179	ND
ACENAPHTHENE	ND	50	306	414	ND	2550	1854	873	2065	3095	2969	ND	1970	3116	2028	3303	ND
FLUORENE	ND	91	305	411	ND	2793	1701	794	1916	2976	3053	2573	1939	3018	1552	3375	2792
PHENANTHRENE	14	139	967	1650	7067	13255	8778	4422	12355	16623	17643	12741	12283	16949	7247	17794	11335
ANTHRACENE	ND	ND	74	128	668	996	746	478	1247	1889	1619	1809	946	1667	1531	1684	647
FLUORANTHENE	ND	50	930	1449	6373	7175	8858	12069	24743	28938	29291	19448	15198	23393	18007	19307	7069
PYRENE	ND	50	126	172	1608	1363	2154	8385	17171	20937	15867	12079	3320	10074	11666	5853	1538
BENZO(A)ANTHRACENE	11	21	58	124	665	868	976	1686	2844	2636	2980	1986	1247	2375	1306	1917	497
CHRYSENE	ND	15	143	272	914	1384	1286	3436	4489	3724	4428	2491	1672	3425	1702	2516	904
BENZO(B)FLUORANTHENE	ND	ND	40	41	36	1504	912	1730	1856	1557	1369	1877	1026	1443	1141	1304	602
BENZO(K)FLUORANTHEN	30	132	140	243	555	595	395	553	576	486	538	576	439	558	348	501	295
BENZO(E)PYRENE	20	46	28	41	35	219	235	775	939	918	658	936	243	559	706	17	139
BENZO(A)PYRENE	ND	21	22	47	112	224	171	241	292	323	244	495	155	272	333	227	94
INDENO(123-CD)PYRENE	ND	ND	ND	81	ND	191	55	109	65	67	ND	87	ND	66	81	61	ND
DIBENZO(A,H)ANTHRACE	ND	ND	75	66	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
BENZO(G,H,I)PERYLENE	31	ND	ND	ND	ND	66	ND	105	67	67	53	77	ND	54	124	ND	ND
TOTAL PAH	129	631	3374	5340	18404	33670	28802	35957	70983	84646	81395	58026	40906	67577	48099	58642	26917

(a) ND = not detected.

Table 2. Concentration of PCB Congeners in Polyethylene Sheets from Elliott Bay

	(Concentration ng/polysheet)															
PCB Congener	Solvent blank	FIELD BLANK	EB-1	EB-2	EB-4	EB-5	EB-6	EB-8	EB-9	EB-10	EB-11	EB-12	EB-13	EB-14 1 meter	EB-14B 5 meters	EB-16	EB-17
8	ND(a)	ND	ND	ND	ND	ND	ND	66	55	34	ND	ND	ND	ND	ND	ND	ND
18	ND	ND	ND	ND	ND	41	19	141	138	86	106	25	ND	84	27	ND	13
28	ND	ND	ND	ND	ND	45	22	139	107	78	116	15	21	85	33	28	ND
52	ND	ND	ND	5	29	52	42	315	276	160	280	42	42	178	71	56	27
49	ND	ND	ND	ND	ND	33	21	146	134	84	132	ND	20	90	36	28	13
44	ND	ND	ND	5	23	31	22	141	122	84	129	ND	20	86	29	24	11
66	ND	ND	ND	ND	ND	39	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
101	ND	ND	ND	ND	ND	ND	32	213	169	104	184	36	40	141	82	42	18
188	ND	ND	ND	ND	ND	ND	ND	104	ND	ND	ND	ND	ND	ND	ND	ND	ND
118	ND	ND	ND	ND	ND	ND	14	128	97	ND	119	ND	21	82	ND	30	16
153	ND	ND	ND	ND	ND	ND	21	124	113	70	121	ND	32	100	82	28	14
105	ND	ND	ND	ND	ND	ND	ND	40	31	21	35	ND	.8	26	9	9	ND
138	ND	ND	2	ND	8	ND	19	104	97	60	99	ND	19	84	51	26	11
128	ND	ND	ND	ND	ND	ND	ND	13	9	ND	ND	ND	ND	8	ND	ND	ND
200	ND	ND	ND	ND	54	116	73	72	135	140	138	50	96	115	26	107	55
180	ND	ND	ND	ND	6	7	ND	29	29	16	29	9	14	33	19	15	6
170	ND	ND	ND	ND	ND	ND	ND	16	15	ND	ND	ND	ND	ND	ND	ND	ND
SUM PCBs	ND	ND	2	10	120	364	283	1789	1525	936	1488	177	332	1109	465	392	185

(a) ND = not detected.

of particles coming from the Duwamish generally follows this pattern. Our results are a good illustration of this overall trend.

Water concentrations can be estimated if 1) the poly sheets have reached equilibrium with the analyte of interest and 2) the K_{poly} is known. To date, we have only determined the K_{poly} for phenanthrene. In addition, we have determined that >90 percent equilibrium is reached within four days for phenanthrene. Therefore, a water concentration for phenanthrene was estimated based on a $\log K_{poly}$ of 4.05. The phenanthrene concentrations in water ranged from a low of 4 ng/L west of Duwamish Head to a high of 79.5 ng/L in the Duwamish River south of Harbor Island. Concentrations around Elliott Bay ranged from about 30 ng/L just west of the West Waterway to about 80 ng/L near Pier 69.

CONCLUSION

SPMDs consisting of polyethylene sheets appear to accumulate HOCs from the water column in a predictable manner. Levels in the Duwamish River for all HOCs analyzed were elevated compared with those measured in Elliott Bay. Water concentrations for phenanthrene ranged from about 4 ng/L to 80 ng/L. These concentrations are consistent with levels of PAHs detected in industrial areas of Puget Sound. Additional K_{poly}s are required for calculation of other HOC water concentrations. Further application of these SPMDs to monitoring HOCs is warranted and could afford a relatively inexpensive, simple, and reliable method for obtaining a time-integrated measure of HOCs in the aquatic environment.

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THE PUGET SOUND PROTOCOLS AND GUIDELINES: AN UPDATE

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INTRODUCTION

For the past two years, the Puget Sound Water Quality Authority has maintained, updated, and distributed the Puget Sound Protocols and Guidelines (PSP&G). The effort to promote use of the PSP&G among concerns collecting environmental data in Puget Sound has been reported at the two previous Puget Sound Research Conferences (Armstrong and Becker, 1988; Faigenblum, Armstrong and Becker, 1991). The purpose of this paper is to provide an update on PSP&G changes that have occurred since early 1991 and to report plans for further revision of some of the chapters.

BACKGROUND

The usefulness of environmental data collected within a region is greatly increased if data from different monitoring efforts are directly comparable. If this condition is met, information from different studies can be combined, and the spatial and time coverage of local databases can be enlarged to provide a more comprehensive evaluation of environmental conditions.

Within the Puget Sound region, environmental agencies are attempting to improve the quality and consistency of environmental information collected in Puget Sound through development and use of the Puget Sound Protocols and Guidelines. The Puget Sound Protocols and Guidelines consist of procedural descriptions developed to encourage scientific investigators to use, where possible, well defined and consistent methods for sampling and analyzing environmental data from Puget Sound (Armstrong and Becker, 1988). The information gathered as part of most Puget Sound environmental surveys, general monitoring programs, and intensive investigations will be of higher quality, and more useful to others, if the recommended protocols are followed whenever possible.

The current PSEP protocols and guidelines document contains 13 chapters which address: general quality control; sediment chemistry; sediment bioassays; station positioning; measurement of metals in water, sediment and tissues; microbial studies; organic compounds in sediment and tissues; subtidal benthic macroinvertebrate assemblages; fish pathology; conventional water quality variables for fresh water; soft-bottom demersal fishes; conventional water quality variables for marine water; and marine mammal tissue analysis (PSEP, 1986).

METHODS AND PROCESS

The process for review, adoption or updating of the protocols involves widespread review by scientists, agency technical staff, and others actively engaged in the topics under consideration. After consensus is reached by a technical review committee, the protocols are forwarded to policy-level managers of PSEP agencies for their agreement. Finally, the recommendations of the policy-level managers in the agencies and organizations appropriate for each protocol are presented to the PSEP Management Committee for final adoption in the Puget Sound Protocols and Guidelines.

Following adoption, PSEP Management Committee members are asked to take the lead in promoting the use of the protocol within their agency or organization. In addition, major organizations that are not members of PSEP are encouraged to use the protocols for collection and analysis of all environmental samples in the basin.

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USE AND IMPORTANCE

The protocols play an important role in the Puget Sound Ambient Monitoring Program (PSAMP). Agencies responsible for collecting data that are used in PSAMP and added to the PSAMP database follow the PSEP protocols and guidelines. Additional studies and data from other investigations or outside agencies are sometimes used to supplement PSAMP data to get a better picture of long-term trends. Such data is more readily compared to PSAMP data if the PSEP protocols are followed.

In addition to the role of the protocols and guidelines in serving the long-term monitoring efforts in the Puget Sound region, the protocols also serve as an important model for other regions to use in developing standardized procedures or when searching for appropriate references for similar efforts. The Authority fills numerous requests for copies of the protocols and guidelines from outside the region.

STATUS UPDATE

Newly Revised Protocol—Marine Mammal Tissue Analysis

In April 1993, the Puget Sound Water Quality Authority began updating the chapter of the Puget Sound Protocols titled *Recommended Guidelines for Sampling Marine Mammal Tissue for Chemical Analysis in Puget Sound.* The review committee was broadened in late 1993 to include two Canadian reviewers, and comments were incorporated into the chapter in March 1994. The revised chapter is currently at the stage of review and adoption by the PSEP Management Committee. Some significant changes in this revision include the following:

- substitution of a new stranding report form;
- addition of the colon to the list of tissues that might be examined;
- some clarification regarding histological examination; and
- acceptable substitutes for methylene chloride for rinsing implements in the field.

Protocol Under Active Revision—Sediment Bioassays

The Puget Sound Water Quality Authority began updating the *Recommended Guidelines for Laboratory Bioassays on Puget Sound Sediments* in July 1993. The purpose of the update was to reconcile this chapter with changes that have been made to bioassays procedures used in the Puget Sound Dredged Disposal Analysis program and to make other changes that have become appropriate since the interim final draft of this chapter was developed in 1991. A workshop was convened in August 1994 to further refine changes to this chapter and to develop a consensus among technical experts. Significant changes that are addressed during this round of revision include the following:

- change of the echinoderm embryo test endpoint to combined mortality/abnormality;
- added flexibility regarding sediment holding times;
- addition of a substitute species (*Ampelisca abdita*) with specific procedures to the Amphipod sediment bioassay to address the issue of sediment grain size complications;
- added warning level advisories for un-ionized ammonia content of sediments; and
- addition of mortality data from the Corps DAIS data base with reference toxicants was added to several of the bioassays.

Protocols Under Active Revision—General QA/QC, Metals and Organics

The Metro Environmental Laboratory (King County Department of Metropolitan Services) is leading the revision of the following three chapters of the PSP&G: "General QA/QC Considerations for Collecting Environmental Samples in Puget Sound" (General QA/QC), "Recommended Protocols for Measuring

Metals in Puget Sound Water, Sediment and Tissue Samples" (Metals), and "Recommended Guidelines for Measuring Organic Compounds in Puget Sound Sediment and Tissue Samples" (Organics).

The Metro Lab routinely analyzes samples from Puget Sound in support of Metro's NPDES permits and marine sediment clean-up activities at combined sewer overflow outfalls. The laboratory's capabilities include field sampling, analyses of chemical and biological parameters, QA/QC, and data management. The Metro Lab brings the routine analytical laboratory perspective to the revision process. And Metro's role in the community has been one of facilitation and consensus building, both of which will be helpful in the revision process.

In the initial development of these three chapters of the protocols, some issues proved difficult to resolve. Of the unresolved issues, some have been barriers to the acceptance and use of the chapters. The revision effort will address these issues and seek to develop consensus among investigators about adopting the revised chapters. New directions under consideration for this revision effort include the following factors that address issues that may have limited protocol acceptance and use in the past:

- Adjustment of the revision process may be made, where appropriate, to improve consensus building, acceptance and use of the protocols. This will involve identification of significant issues earlier in the development process.
- Difficulties in implementation and technical feasibility will be addressed, e.g., unrealistic detection limits for marine samples. The review will examine appropriate methods that may be employed for low-level work and for higher-level work.
- Conflicting needs of various programs that collect data in the region will be analyzed from the perspective of differing analytical methods and difficulties in comparing data from different programs.
- Areas of insufficient guidance will be identified. The material in the chapters will be augmented to ensure that data quality objectives are adequately defined and that proper guidance is provided for choosing analytical methods necessary to meet those objectives.
- Organization of information within the three chapters will be improved. Information on sample collection will be collated so that guidance on sample collection is consistent for all parameters.

A new performance-based approach to QA/QC and method selection has been proposed at the national level (IAETL, 1994). EPA's Environmental Monitoring Management Council (EMMC) is considering approaches for piloting or implementing the use of performance-based methods as part of a comprehensive strategy to reduce the confusing array of similar measurement methods adopted under various regulatory programs. In addition, a performance-based method system will allow the regulated community to use new or emerging technologies to meet the monitoring requirements of the regulations.

Metro plans to learn from those engaged in this debate, and proposes consideration of this approach for revision of the General QA/QC chapter. Some view this performance-based approach as highly desirable because the quality of the data can be determined regardless of a specific method. It also puts more emphasis on project planning and documentation of data quality objectives so that the end use of the data can be part of the method selection criteria.

Two definitions for performance-based methods are currently proposed by EMMC. The first is their original definition and is comprehensive:

> A monitoring approach that permits the use of appropriate analytical methods that meet established, demonstrated method performance standards based on data quality needs. Minimum required elements of performance, such as precision, accuracy, sensitivity, specificity (interferences) and detection limit, must be specified and an available method must be shown to meet the method performance standards.

A second, more general definition was developed as the EMMC considered the matter further:

> An analytical procedure containing the necessary method performance specification to assure the desired quality of results.

Metro will use these definitions as a starting point for consideration of this new approach in the efforts to revise the General QA/QC chapter of the Puget Sound Protocols.

The content of the Metals and Organics chapters depends on the outcome of the discussions around the performance-based approach to method selection. If this approach is selected, the method details would not be specified in these two chapters, but rather, a list of documented methods (and their detection limits and typical uses) would be provided as options. The laboratory would choose a method based upon the method selection criteria, and document the quality of the data produced by that method. Practical guidance on using the methods to analyze real life marine samples would supplement the method selection information.

New Protocol—Estuarine Habitat Assessment Protocol

Late in 1991, EPA Region 10 published as a separate document the *Estuarine Habitat Assessment Protocol*, which was prepared under grants by Charles A. Simenstad and Curtis D. Tanner of the Wetland Ecosystem Team, Fisheries Research Institute of the University of Washington, Ronald M. Thom of Battelle Marine Sciences Laboratory, and Loveday L. Conquest of the Center for Quantitative Science, University of Washington (1991). This protocol was developed in response to the need for procedures that quantitatively assess the function of estuarine wetlands and associated nearshore habitats for fish and wildlife.

The following are some key points extracted from this protocol:

- "The functional approach was taken in preference to simply assessing fish and wildlife use because the later, usual approach to habitat assessment does not measure habitat quality directly, nor does it identify the characteristics of the habitat that explicitly promote fish and wildlife utilization."
- "The goal of the protocol is to initiate systematic, on-site measurement of estuarine wetland and nearshore habitat function for fish and wildlife utilization by assessing the attributes of the habitats identified as being functionally important to fish and wildlife."
- "The protocol is intended as a supplement, not a replacement, to more comprehensive but basically qualitative procedures for assessing overall habitat quality (e.g., Wetland Evaluation Techniques, and Habitat Evaluation Procedures)."

Investigators involved in estuarine habitat assessment studies within the Puget Sound region are encouraged to examine the relevance of this protocol to their studies.

AVAILABILITY AND INTEREST IN REVIEWS

The Puget Sound Water Quality Authority makes available electronic copies (3-1/2 inch floppy disk in Word Perfect format) of the Puget Sound Protocols and Guidelines to investigators and others involved in collection and review of environmental data. Those interested in obtaining copies of the 13-chapter Protocols document on disk may call the Authority's publication specialist at (206) 407-7329. Those interested in obtaining a copy of the Estuarine Habitat Assessment Protocol may contact Michael Rylko at EPA Region 10 (206) 553-4014.

Currently, the Puget Sound Water Quality Authority is revising several chapters, including those dealing with sediment bioassays, and conventional marine water column variables. Other chapters will come up for revision periodically. If you have expertise in any of the topic areas and would like to be involved in current or future revisions, contact the Authority at 1-800-54-Sound.

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ESTIMATION OF MINIMUM DETECTABLE TREND IN WATER QUALITY VARIABLES IN PUGET SOUND AREA RIVERS

William James Ehinger[1]

The most valuable use of water quality monitoring data is the detection of changing conditions, i.e., trend analysis. Reliable detection of changes in relatively clean waters is necessary for early intervention to prevent serious degradation, while trend analysis permits one to determine the effectiveness of pollution control measures on conditions in degraded streams. However, trend analysis is not a simple matter. Rates of change in water quality variables are usually only a few percent per year, and these are often masked by the variability that results from large fluctuations in flow, seasonal effects, water collection techniques, and laboratory analysis. In addition, long-term climatological trends can affect in-stream variables and produce apparent trends (see Gilbert, 1987; Ward et al., 1990). The magnitude of change that can be detected is heavily dependent upon the extent to which the variability in the data (due to climatological or other "non-trend" factors) can be reduced. There are a number of techniques used to reduce or to control for this noise in the data. This paper briefly outlines the factors affecting trend analysis, then demonstrates one technique to reduce variability and how it may be used both to lower the minimum detectable trend and to detect a false trend in a sample dataset. Finally, I calculate the minimum detectable trend, after adjusting for flow, for several variables in Puget Sound area rivers using data from the Washington Department of Ecology's Ambient Monitoring Network.

Linear trend analysis is a form of hypothesis testing of the model

$$y_t = \mu + \Delta\mu * t/t_f + \varepsilon_t \qquad 1)$$

where

y_t = the value of the monitored water quality variable at time, t
μ = the mean at the beginning of the time period
$\Delta\mu$ = the change in the mean over the time period,
t = the time elapsed since the beginning of the time period,
t_f = the length of the time period,
ε_t = a stochastic error term (Lettenmaier, 1977).

The hypothesis to be tested is:

H_0 (null hypothesis): $\Delta\mu = 0$ (no change in the mean value),
and H_a (alternate hypothesis): $\Delta\mu \neq 0$ (a change has occurred).

Given these two choices and the two states of nature, four combinations are possible (Figure 1), and two types of error may occur:

Type 1 error occurs when the test indicates that the mean value has changed, whereas in reality it has not. The α-value (confidence level) for that test is the probability that this type of error has occurred when H_0 has been rejected.

Type 2 error occurs when the test indicates that there has been no change in the mean (H_0 accepted), whereas in reality the mean has changed. The probability of Type 2 error is β, and the power of the test (1- β) is the probability of detecting a change in the mean value when it has actually changed.

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		Test result	
		H_0 is true	H_a is true
State of nature	H_0 is true	$P = 1-\alpha$	$P = \alpha$ Type 1 error
	H_a is true	$P = \beta$ Type 2 error	$P = 1 - \beta$

Figure 1. Four combinations of the true "state of nature" and test results are possible. Acceptable α and β levels should be chosen a priori *and will help clarify the interpretation of non-significant statistical test results.*

One must be aware that acceptance of the null hypothesis does not "prove" that no change has occurred but may only indicate that the magnitude of trend is too small to be detected with the particular statistical test and dataset used. Before concluding that conditions at a monitoring site have not changed, the analyst should determine:

1) the power of the statistical test to detect a reasonable change in the variable of interest; and

2) the magnitude of change that could be detected at a given power (90 percent, for example) with that statistical test and dataset.

For example, if the power of the test were very low, then a finding of no significant trend has little real meaning because there was a low probability of detecting a trend. Or if the magnitude of a change that the test could detect with 90 percent probability is very large, this finding of no change has little practical meaning to the water quality manager.

FACTORS AFFECTING STATISTICAL POWER

Although the model in Equation 1 is based upon a two-tailed t test (and the assumptions of normally distributed data inherent to this test), its application to the nonparametric tests commonly used for trend analysis is warranted because:

1) The nonseasonal, nonparametric tests, i.e. Spearman's rho, Mann-Whitney's (Lettenmaier, 1976), and Sen/Ferrel (Ehinger, 1995) are approximately as powerful as the t test when the data are normally distributed and non-seasonal, and more powerful when the data are not normally distributed (as is frequently the case with water quality data); and

2) when seasonal data necessitate the use of a seasonal test (Seasonal Kendall test), similar power may be maintained by increasing the risk of Type 1 error from 0.10 to 0.20 (Ehinger, 1995).

The power of a two-tailed t test of the hypothesis, where values of ε_t are independent and normally distributed, is (Breiman, 1973):

$$\text{Power} = 1-\beta = F\,(N_T - T_{1-\alpha/2,\, n-2}) \qquad 2)$$

where

F = the cumulative distribution function of the standard normal probability distribution,
T = the value of student t for $1-\alpha/2$ with n-2 degrees of freedom, and

$$\Delta\mu = s_{obs} * \frac{n*\sqrt{12}}{\sqrt{n*(n+1)*(n-1)}} * (T_{1-\beta,\,n-2} + T_{1-\frac{\alpha}{2},n-2})$$

3)

where

n = sample size,

$\Delta\mu$ = the absolute value of the change in the mean value over the period of record (*i.e.*, trend magnitude)

s_{obs} = the observed standard deviation of the detrended, deseasonalized data (Lettenmaier, 1976).

Equations 2 and 3 may be combined and rearranged to give:

$$\Delta\mu = s_{obs} * \frac{n*\sqrt{12}}{\sqrt{n*(n+1)*(n-1)}} * (T_{1-\beta,\,n-2} + T_{1-\frac{\alpha}{2},n-2})$$

4)

From Equation 4 one can see that the magnitude of trend that is likely to be detected is dependent upon:

1) the desired power to detect trends ($1-\beta$), or how confident we wish to be that the test will detect trends of a given magnitude;

2) the chosen confidence level ($1-\alpha$), or how confident we wish to be that the trends that are detected actually exist and are not due to random error;

3) the number of observations (n, assuming that no significant autocorrelation exists); and

4) the variability in the data (s_{obs}). This includes the true, in-stream variability plus that added by the collection, processing and laboratory analysis of the water.

The power and confidence level are normally chosen *a priori* and are based upon the relative risks of not detecting a trend that exists and of falsely detecting a trend where one does not exist. Sample size has a profound impact upon trend detection. Lettenmaier (1982) recommended a minimum of five years of monthly data (n = 60) in order to have a large enough sample size to detect changes of a reasonable magnitude while reducing the probability of significant autocorrelation in the data.

The final factor affecting trend detection is the variability of the data. The variability observed at a specific site over time represents variability due to water collection, field and laboratory processing and analysis, seasonal and natural processes, human-induced processes (which often cause the real changes in the mean value of the variable that are of interest to environmental managers) and stochastic events. The variability due to collection, processing, and lab analysis is minimized via a good sampling design and strict adherence to field and laboratory protocols. After the data have been collected, it is the analyst's job to reduce the variability that arises from seasonal and natural processes and then determine whether human-induced processes have resulted in a change in the variable of interest. In effect, we try to lower the signal (trend)-to-noise (other sources of variability) ratio in order to increase the likelihood of detecting the signal amidst the noise.

USE OF EXOGENOUS VARIABLES TO REDUCE VARIABILITY

The values of several commonly measured water quality variables are often correlated with flow. Consider a site where the flow regime has changed over the monitoring period, and trends are detected in other variables that are correlated with flow (e.g., suspended solids, nitrate/nitrite-N, total phosphorus, etc.). If the hypothesis is, "Has a change occurred in variable Y?", then this analysis is satisfactory. However, if the hypothesis is, "Has a change occurred in variable Y that is not related to flow?" or "Has the relationship between the variable and flow changed?", then this analysis is incomplete. Variability due to flow may be removed by linear regression of the data followed by a trend analysis on the residuals (Harned et

al., 1981; Hirsch et al., 1981). Data transformations are often necessary to make the relationship linear and to satisfy the assumptions of homogenous variance. This technique can not only lower the minimum detectable trend but also help identify the cause of observed trends.

Data collected from the Deschutes River, near Olympia, are used below to illustrate the first point. There is a strong positive relationship between total suspended solids concentration and flow (Figure 2), where high flows tend to produce high sediment concentrations. Obviously, this relationship is heavily influenced by two high flow observations, but a $\log_{10}$-transformation adequately describes the relationship while stabilizing the variance across the range of flow values (Figure 3). The regression residuals are calculated as the observed value minus the predicted value and represent the portion of the variability in suspended sediment concentration not accounted for by flow. Figure 4, a time series of both the raw data and the untransformed residuals, illustrates the of reduction in variability of the residuals (i.e., the magnitude of the peaks and valleys of the residuals is lower). Based upon Equation 4, (assuming power = 0.90, confidence level = 0.90, and five years of monthly data) the magnitude of detectable trend was reduced from approximately 56 to 48 mg L^{-1} per five-year period.

The same procedure may be used with other variables to discern real trends from artifacts in the data. For example, an increasing trend was detected in the raw water temperature data from the Entiat River in central Washington. A closer examination of the data showed that over the past decade the time of day when the data were collected had shifted from the morning to the afternoon (Figure 5). Higher afternoon air temperature means higher water temperature, especially in the summer months. When this source of variability was removed from the data, no significant trend was detected. Because similar time-of-day correlations can occur with dissolved oxygen concentration and pH measurements, the analyst should inspect these data closely.

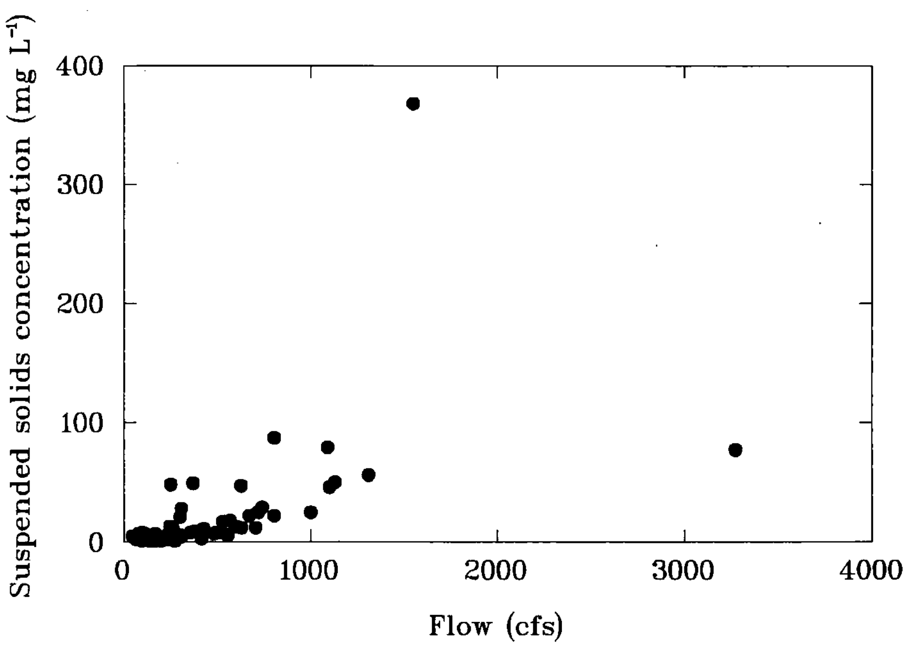


Figure 2. Suspended solids concentration vs. flow. The relationship between raw water quality variables is often heavily influenced by a few extreme events (high flows).

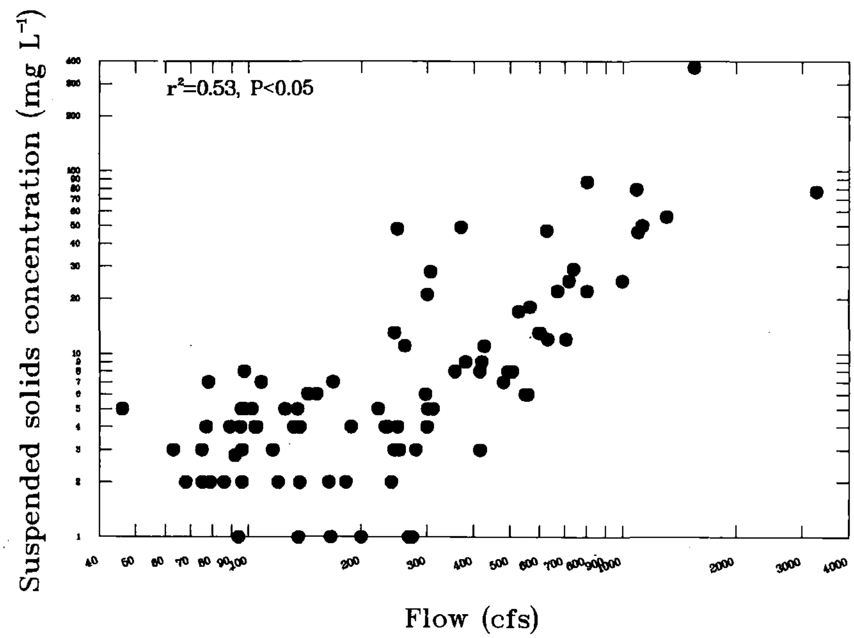


Figure 3. A $\log_{10}$-transformation is often sufficient to linearize the relationship and stabilize the variance. However, more complex, higher-order models may be necessary.

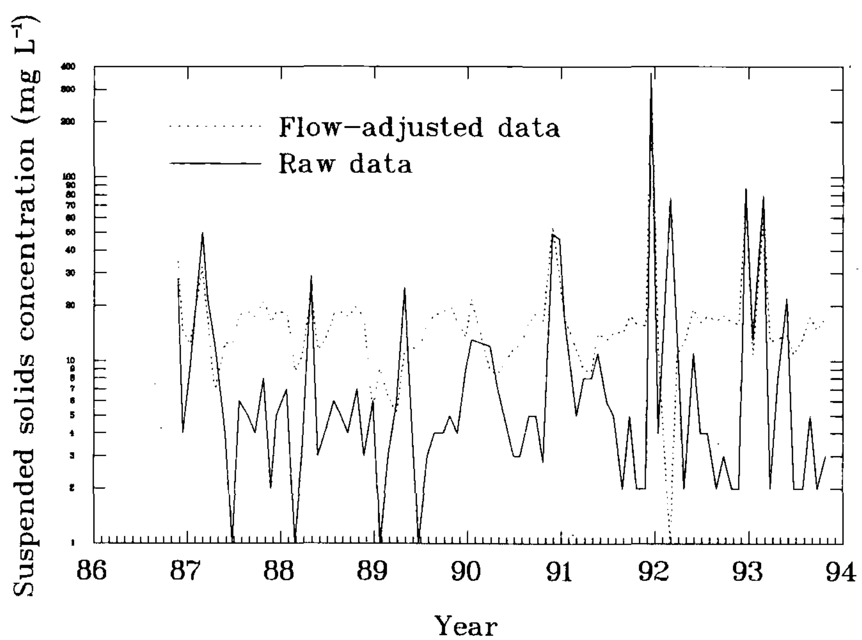


Figure 4. This time series of both the raw data and the flow-adjusted data show the reduction in variance achieved by removing the effect of flow.

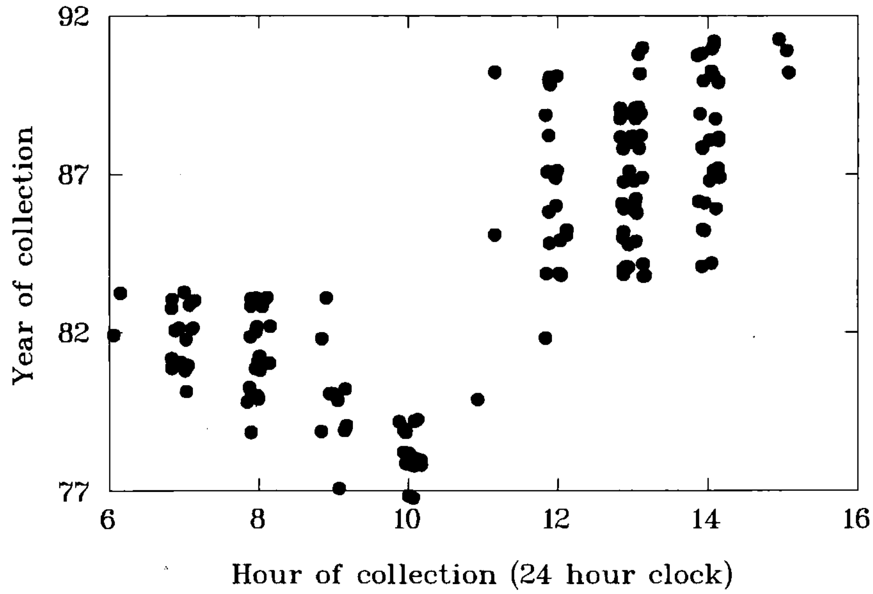


Figure 5. A change in the sampling protocol, such as a change in the time of water collection, can have profound impacts upon the statistical analysis. In this case a shift from morning to afternoon collection resulted in a false positive increasing trend in temperature.

MINIMUM DETECTABLE TRENDS IN PUGET SOUND AREA RIVERS

Using the procedures shown above, we calculated the minimum detectable trends in the raw data ($\Delta\mu_{raw}$), the regression residuals after the correlation with flow has been removed ($\Delta\mu_{flow\text{-}adj}$) and the percent improvement in trend detection, ($[\Delta\mu_{raw} - \Delta\mu_{flow\text{-}adj}]/\Delta\mu_{raw}*100$), that this procedure provides for nitrate +nitrite-N and suspended solids concentrations. Data were collected by the Department of Ecology's Ambient Monitoring Network and include all Puget Sound area sites with at least five contiguous years of monthly data since 1985 (see Appendix A). These minimum detectable trends represent the magnitude of trend over a five-year period that may be detected 90 percent of the time with a 10 percent chance of falsely detecting a trend (assuming a monthly sampling frequency over the five-year period). Trends of a much smaller magnitude may be detected but at a lower frequency (power).

Because the variability of water quality data is often positively correlated with mean concentration, the minimum detectable trend is generally lower in streams with low mean concentration. This holds true for both nitrate/nitrite-N and suspended solids concentration (Figures 6 and 7). The minimum detectable trend in the flow-adjusted nitrate/nitrite data ranged from approximately 22 $\mu g\ L^{-1}$ to more than 300 $\mu g\ L^{-1}$ per five years (Figure 6a). Improvement due to flow-adjustment ranged from 0 percent to 33 percent (Figure 6b). For suspended solids the minimum detectable trend ranged from five mg L^{-1} to nearly 800 mg L^{-1} per five years (Figure 7a) and percent improvement ranged from 0 percent to 28 percent. In this example, the percent reduction was dependent upon the strength of the correlation of concentration with flow. Further improvements in trend detection are possible by removing variability related to other exogenous variables (e.g., antecedent rainfall, output variables of watershed models, etc.), by applying more complex models, or by using multiple regression techniques (Alley, 1988).

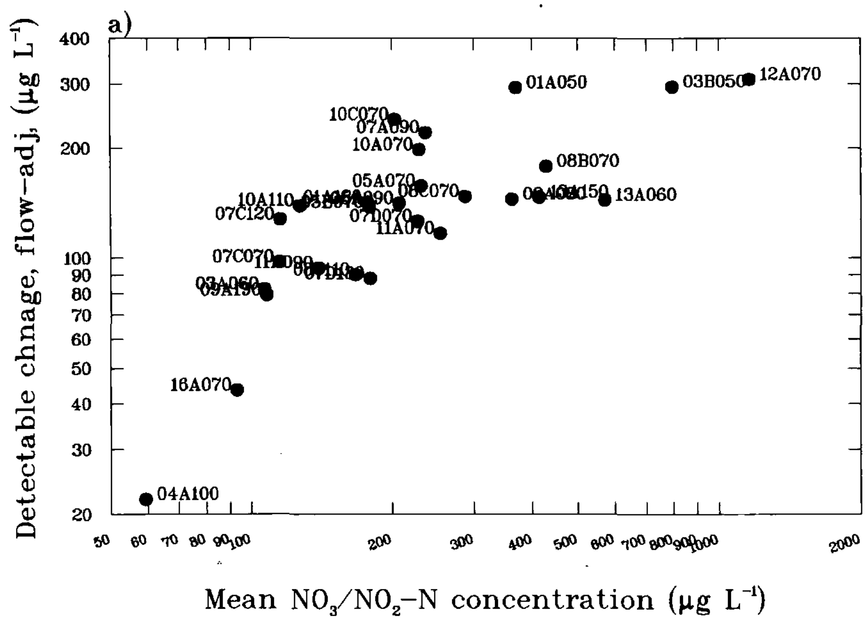
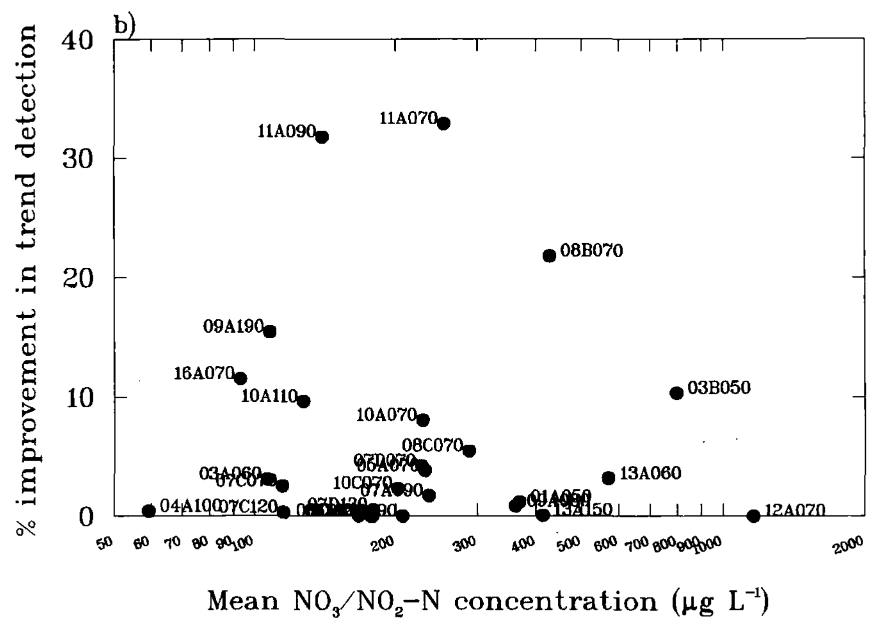


Figure 6. a) Minimum detectable change in nitrate+nitrite-N concentration over a five-year period, after flow-adjustment, (assuming α=0.10, β=0.10, n=60, and no significant autocorrelation) presented as a function of mean concentration



b) Percent improvement in minimum detectable trend due to flow adjustment (see text)

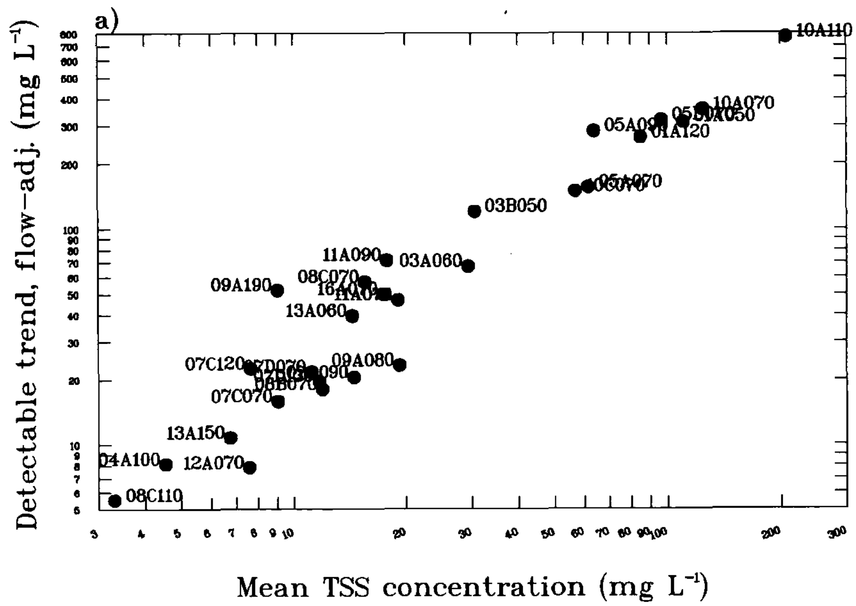
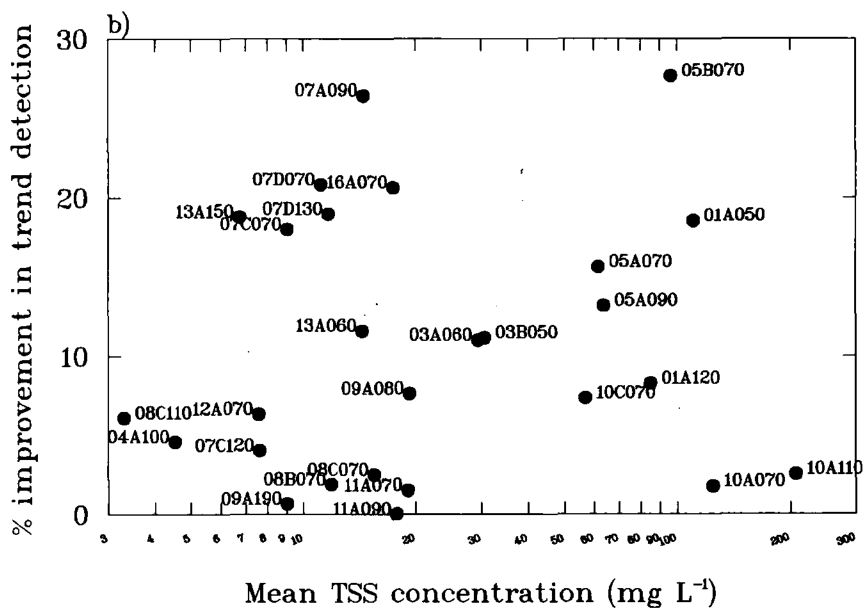


Figure 7. a) Minimum detectable change in suspended solids concentration over a five-year period, after flow adjustment (assuming α=0.10, β=0.10, n=60, and no significant autocorrelation), presented as a function of mean concentration



b) Percent improvement in minimum detectable trend due to flow adjustment (see text)

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APPENDIX A
RIVER AND STREAM SAMPLING STATIONS USED IN FIGURES 6 AND 7

Station ID	Location	Station ID	Location
01A050	Nooksack River @ Brennan	08B070	Sammamish River @ Bothell
01A120	Nooksack River near Lynden	08C070	Cedar River @ Renton
03A060	Skagit River near Mount Vernon	08C110	Cedar River near Landsburg
03B050	Samish River near Burlington	09A080	Green River @ Tukwila
04A100	Skagit River @ Marblemount	09A190	Green River @ Kanaskat
05A070	Stillaguamish River near Silvana	10A070	Puyallup River @ Meridian St.
05A090	South Fork Stillaguamish River @ Arlington	10A110	Puyallup River @ Orting
		10C070	White River @ Sumner
05B070	North Fork Stillaguamish River @ Cicero	11A070	Nisqually River @ Nisqually
07A090	Snohomish River @ Snohomish	11A090	Nisqually River above Powell Creek
07C070	Skykomish River @ Monroe	12A070	Chambers Creek near Steilacoom
07C120	Skykomish River near Gold Bar	13A060	Deschutes River @ E Street Bridge
07D070	Snoqualmie River near Carnation	13A150	Deschutes River near Ranier
07D130	Snoqualmie River @ Snoqualmie	16A070	Skokomish River near Potlatch

MEASURING BIOACCUMULATION AND BIOEFFECTS IN TRANSPLANTED BIVALVES AS A POLLUTION MONITORING TOOL IN PUGET SOUND

Michael H. Salazar[1] and Sandra M. Salazar[2]

INTRODUCTION

Biomonitoring that includes measurements of bioaccumulation and bioeffects in resident or transplanted bivalves is a potentially powerful tool for monitoring pollution. Because bivalves accumulate contaminants, they are good indicators of environmental conditions. They can also be used as indicators of environmental effects by measuring biological processes such as growth. In Puget Sound, routine monitoring of contamination in resident bivalve tissues has been used to assess only public health concerns. The State of California has been monitoring accumulation of contaminants in both resident and transplanted mussels since 1977, and the National Oceanic and Atmospheric Administration (NOAA) has measured bioaccumulation in resident mussels and oysters in coastal regions of the United States since 1984. Both the State of California and NOAA have used these data to identify potential problem areas and track the status and trends of contamination. Although emphasis has been on measuring bioaccumulation in bivalve tissues, measurements of bioeffects such as growth are relatively easy, particularly in caged animals. The addition of a bioeffects component would benefit these and other pollution monitoring programs.

Existing environmental monitoring programs in Puget Sound could provide more meaningful data to regulatory decision-makers if they included routine monitoring of resident and transplanted bivalves. These data could be used to meet regulatory requirements, and to facilitate the understanding of mechanisms that affect the bioaccumulation of contaminants and associated biological effects. Transplanting bivalves in cages combines the advantages of environmental realism from field monitoring with the advantages of experimental control from laboratory bioassays. Test animals can be strategically placed along contamination gradients to provide a more complete sampling matrix over space and time (Figure 1). Compared to measuring natural populations, this approach facilitates hypothesis testing, and the exposure period of caged bivalves is clearly defined. In addition to concentrating chemicals in their tissues, bivalves are particularly well-suited to field testing because they are sedentary; i.e., they are easy to collect, cage, and measure. In Puget Sound, mussel and oyster farms provide a readily available source of uncontaminated animals in a relatively uniform size range.

PUGET SOUND EXAMPLES

Between 1975 and 1994, several studies were conducted in Puget Sound using transplanted bivalves as a pollution monitoring tool (Table 1). In addition, mussel transplants have been used to measure growth rates for other applications such as mariculture, carbon cycling, and the effects of neoplasia, but this work will not be discussed here. Only the eight pollution studies with bioaccumulation data are summarized in Table 1. Mussels were transplanted in the water column in every bioaccumulation study except one (Malins et al., 1982). In the Malins et al. (1982) study, clams were transplanted directly into the sediment. Collectively, these studies demonstrate that transplanted bivalves can be used to assess contamination and effects in the sediment and the water column. As in most early field monitoring of bivalves, and even current routine monitoring by NOAA and the State of California, these Puget Sound studies were primarily intended to measure bioaccumulation, not bioeffects. In most studies, survival was not even reported. The most important contributions of each study are summarized below.

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Table 1. Summary of bivalve transplant studies in Puget Sound

Study Year	Location	Sites	No. Days	Tissue Toxics	Bivalve Bioeffects	No. Animals	Summary of Results	Reference
1975	Duwamish	2	49	PCBs	NM	400	High PCBs in tissues of Duwamish mussels; rates of accumulation & depuration estimated; tissues of residents & transplants similar.	Calambokidis et al., 1975
1975 1976	Hood Canal Hood Canal	4 4	4 4	Metals Metals	Byssal thread production	200 200	Low metals in Hood Canal mussel tissues; no difference in metals or threads among sites.	Peeling et al., 1976
1976	Eld Inlet; Duwamish	1	89	PCB	NM	300	High PCBs in resident Duwamish mussels; exponential depuration after transplanting to Eld Inlet; congeners had different depuration rates.	Calambokidis et al., 1979
1976	Elliott Bay	2	21	PCBs	NM	240	No significant difference in tissue PCBs at beginning/end of test at dump site; significant difference between reference & dump site at end of test.	Stout and Lewis, 1977
1981	Hylebos Waterway; Port Susan	2	71	PAHs	Histopathology	115	High PAHs in clams transplanted in Hylebos Waterway sediment compared to Port Susan reference sediment; no histopathological effects.	Malins et al., 1982
1982	Commencement Bay; Sequim	2	168	Metals	Condition index	500	Mussels transplanted from Sequim to Tacoma accumulated high metals; reciprocals depurated metals. Inverse relationship exists between water/tissue metals and mussel condition index.	Roesijadi et al., 1984
1991	Harbor Island; Carr Inlet	14	90	Metals, organics, TBT	Growth	3500	Harbor Island mussels had higher tissue burdens of chemicals, lower growth than reference site; inverse relationship between sediment/tissue chemistry and mussel growth.	Salazar et al., 1994
1994	Sinclair Inlet; Holmes Harbor	5	90	Metals, organics, TBT	Growth	1500	High PCBs in tissues of Sinclair Inlet mussels; whole animal and shell growth higher in Sinclair Inlet; tissue growth higher in Holmes Harbor.	URS, 1994

(NM = not measured).

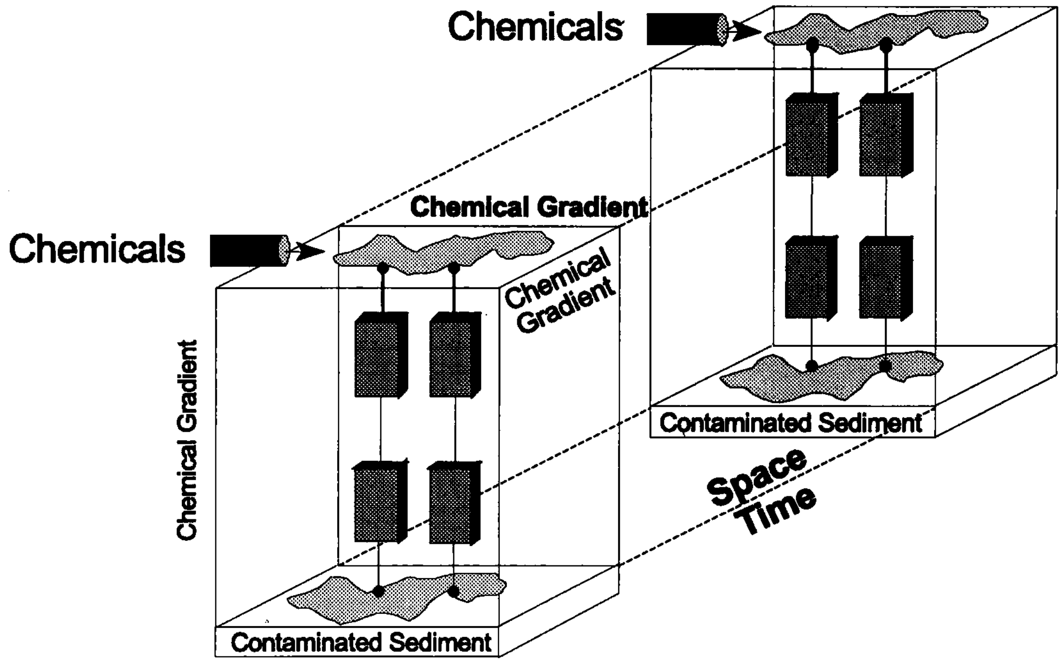

Figure 1. Sampling space and time with bivalve transplants along gradients of chemical contamination. Figure illustrates two suspected sources, two sites (two contaminated sites or one contaminated and one reference), two depths, or two sampling intervals.

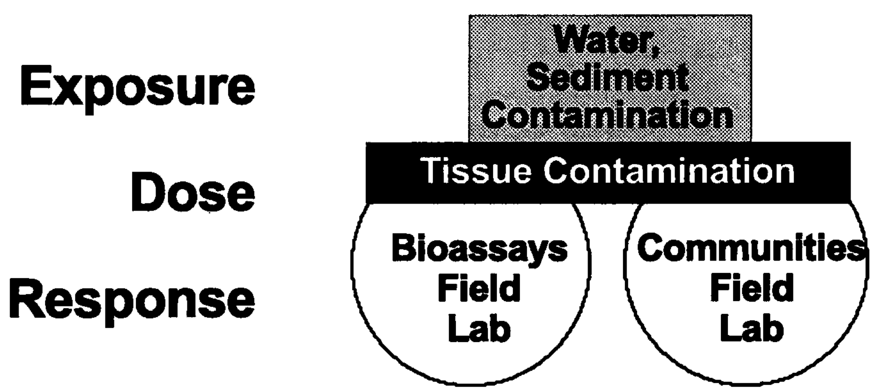

Figure 2. Exposure-Dose-Response triad showing the link between contamination in the environment, contamination in tissues, and biological responses. This link forms the basis of this integrated monitoring approach.

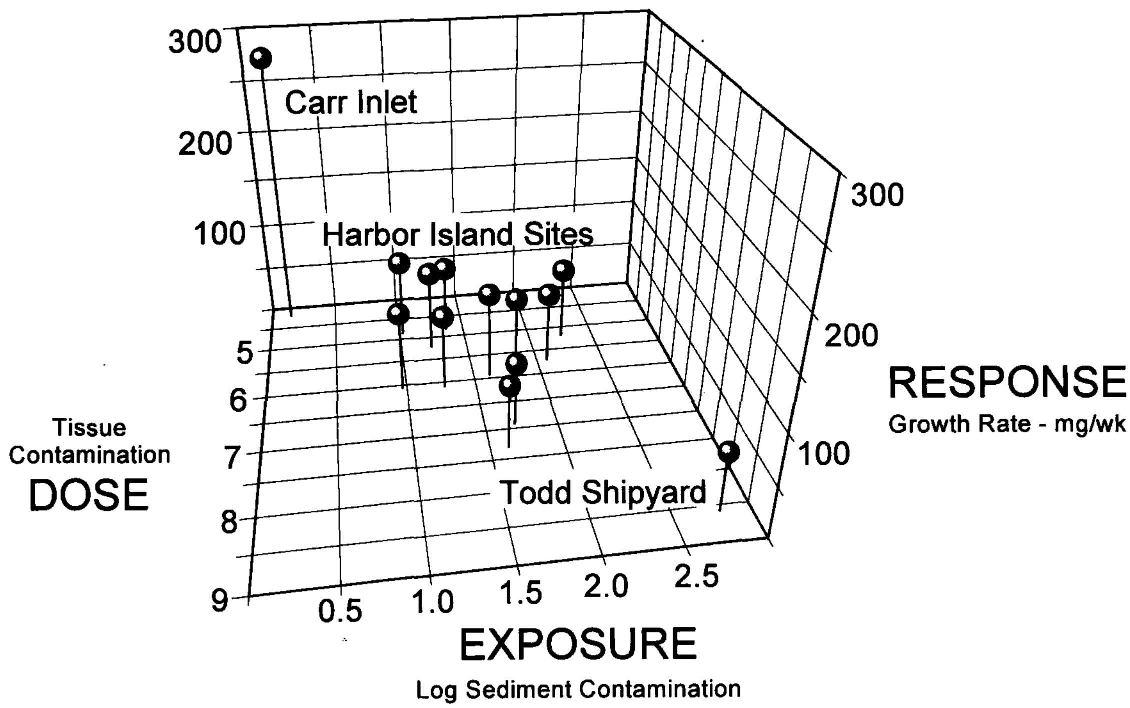

Figure 3. Using the Exposure-Dose-Response Triad of sediment and tissue contamination and mussel growth to evaluate contaminated sediment at the Harbor Island Superfund site in Puget Sound

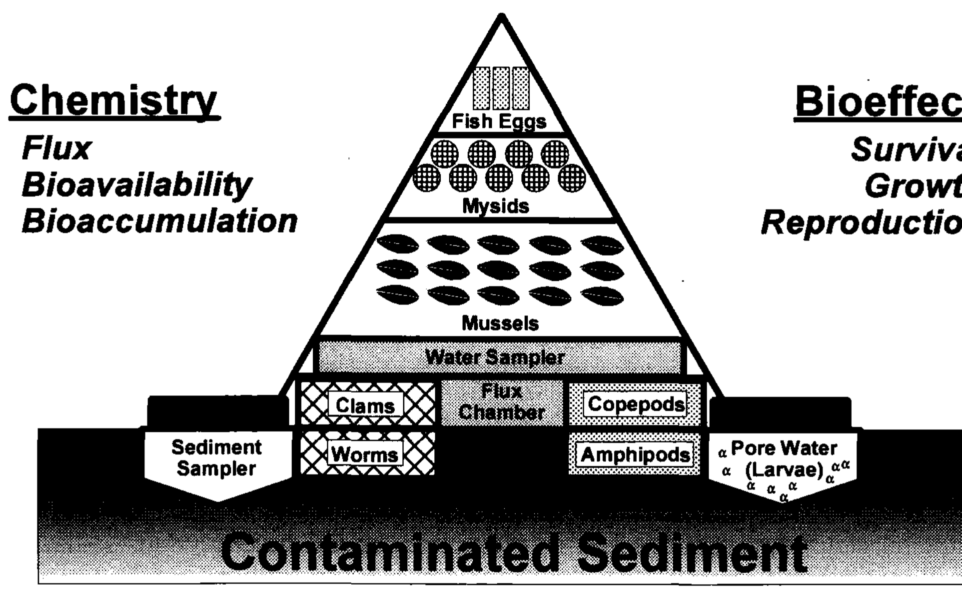

Figure 4. Integrated benthic sampler using bivalve transplants. Also shown are transplanted crustaceans, worms, larvae, and fish eggs, in addition to sediment and water sampling devices.

Calambokidis et al. (1975, 1979) conducted two mussel transplant studies in Puget Sound. In the first study, they found that polychlorinated biphenyl (PCB) concentrations in resident mussels were similar to transplanted mussels after a seven-week exposure period at both contaminated and uncontaminated sites. Because of the similarity in PCB concentrations, transplanted mussels were considered to be a reasonable surrogate for natural populations. The accumulation of high PCB concentrations in mussels at the contaminated site was correlated with known sources. The second study showed that different PCB congeners had different rates of depuration and that in general, depuration was exponential. Peeling et al. (1976) combined bioaccumulation measurements with non-destructive, multiple measurements of bioeffects. Although no significant differences were found among stations in accumulated metals or byssal thread production, it is likely that the four-day exposure period was too short for contaminants to reach equilibrium with the tissues, or for mussels to show measurable adverse effects.

Two studies were conducted by the National Marine Fisheries Service (NMFS) between 1976 and 1981. Based on tissue residue data, the first study (Stout and Lewis, 1977) concluded that there was no significant input of PCBs to Elliott Bay from the disposal of dredge material; however, this conclusion is misleading. Although there was no significant difference between initial and final PCB concentrations in mussels transplanted to the disposal site, variability in size and initial PCB concentrations could account for the inability to detect significant differences. Their data show a statistically significant difference when the final PCB tissue concentrations at the disposal and reference sites are compared. The second NMFS study (Malins et al., 1982) was the first to use infaunal clams, and showed significant accumulation of bioavailable contaminants in sediment. Although no histopathological effects were observed, the 71-day exposure period may have been too short to demonstrate measurable adverse effects.

The Roesijadi et al. (1984) experiment was the most sophisticated of all the early studies and provided information on rates of accumulation and depuration for several metals, differences among sites, and measurements of seawater chemistry, tissue chemistry, and mussel condition. In 1991, a mussel transplant study was conducted in Commencement Bay as part of the Environmental Protection Agency (EPA) Superfund process. However, the mussel tissues were not analyzed because survival was very low (23%). Also in 1991, EPA conducted a transplant study to evaluate contaminated sediments around the Harbor Island Superfund Site by transplanting mussels 1 meter off the bottom (Salazar et al., 1994). This pilot study utilized measurements of contaminants in tissues and mussel growth, and included an analysis of sediment chemistry data that had been previously collected. It was the first bivalve transplant study in Puget Sound in which all priority pollutants and bioeffects were measured at multiple sites.

The bioaccumulation and bioeffects approach (Salazar and Salazar, 1995) used in the EPA pilot study was also used recently to evaluate contaminated sediment in Sinclair Inlet, adjacent to the Puget Sound Naval Shipyard (URS, 1994), and in the tidal channels adjacent to the Tulalip Landfill. Mussel survival in both the EPA pilot study and Sinclair Inlet study was high (from 80 percent to more than 90 percent). Low survival (approximately 50 percent) was reported for the Tulalip study; the tissues from this study have not yet been analyzed for contaminants. The Tulalip Landfill study is significant because it is the first intertidal transplant in Puget Sound, and it is the largest study conducted to date (approximately 5,000 animals).

EXPOSURE-DOSE-RESPONSE TRIAD

As discussed above, measuring bioaccumulation and growth with *in situ* bioassays is a powerful pollution monitoring tool. The best potential application of this tool in Puget Sound is to integrate it with a more comprehensive approach to assessing water and sediment quality: the exposure-dose-response (EDR) triad. The EDR triad approach adds two important components that are missing from the approaches currently used in Puget Sound that are based on a sediment quality triad: *in situ* bioassays and bioaccumulation. The sediment quality triad integrates only sediment chemistry, laboratory bioassays, and benthic community analysis. The *in situ* bioassay component of the EDR triad approach could be fulfilled with bivalve transplants and with measurements of bioaccumulation and bioeffects. Figure 2 shows the EDR triad. It combines water and sediment chemistry data to estimate chemical exposure, measurements

of bioaccumulation to estimate chemical dose, and a combination of laboratory and field bioassays, as well as community studies in the laboratory and the field, to estimate biological response.

This integrated EDR approach eliminates some deficiencies in current methods and is cost-effective to implement. For example, one problem with analytical measurements of environmental media is that not all contaminants in water or sediment are biologically available. Therefore, chemical measurements are not necessarily good estimators of the contaminant dose. Laboratory bioassays are not always good predictors of bioaccumulation or bioeffects because test conditions are not necessarily representative of site-specific conditions, and artifacts can be introduced due to manipulations of water and sediment. These problems can be avoided with *in situ* bioassays. Although benthic community analyses provide a true indication of site-specific conditions, there are many factors other than contaminants that could affect the observed distributions. Caged bivalves are affected by those same natural factors that complicate interpretation of benthic community data. The benefits gained by conducting bivalve transplant studies include a greater ability to conduct manipulative experiments, using the same species in various areas of concern, and using the ability of bivalves to filter water and process sediment particles. In addition, bivalves are relatively easy to cage, and growth measurements can be made using only a calipers and analytical balance. The major costs are associated with chemical analyses of bivalve tissues.

PUGET SOUND APPLICATIONS

Generic applications of the bivalve transplant approach to monitor both bioaccumulation and bioeffects include assessments of: 1) site-specific differences; 2) temporal and spatial variability; 3) short- and long-term trends; 4) exposure pathways and source identification; and 5) dose-response estimates. In addition to site-specific differences, one-time tests can provide information on exposure pathways and source identification. Multiple sequential tests are needed to for the other applications. A graphical example of the discriminating power of the EDR triad using mussel transplants is shown in Figure 3 using data from the Harbor Island Superfund site. It shows the relative importance of sediment chemistry (exposure), tissue chemistry (dose), and mussel growth (response) in identifying site-specific differences. All of the Harbor Island sites were distinguished from the Carr Inlet reference site. One Harbor Island site (Todd Shipyard) was more different than the others.

Programmatic applications of the bivalve transplant methodology could include monitoring dredging, capping, and disposal operations, site characterization, estimates of bioaccumulation potential, sediment and water quality monitoring, and evaluations of biological resources. Transplanted bivalves can also be used in risk assessments, evaluations of cleanup and restoration activities, and oil spills; before, during and after significant events. They can also be used to monitor specific contaminants such as pesticides, PCBs, dioxins, oil, and metals. Transplanted bivalves have been required by the Washington Department of Ecology to assess bioaccumulation and bioeffects at the Puget Sound Naval Shipyard and by the EPA to evaluate the Tulalip Landfill.

The EDR triad need not be limited to sediment evaluations, and test animals need not be limited to bivalves. The most comprehensive approach would integrate other species and community assessments as part of the evaluation. The biological response could be estimated through a combination of laboratory bioassays, benthic community analyses, and laboratory microcosm manipulations of populations. Benthic communities could even be transplanted *in situ*. Suggested species for this EDR triad include those that have been used most frequently in laboratory and field bioassays: mysids, copepods, amphipods, fish eggs, bivalve and echinoderm larvae, and worms. Water column and infaunal bivalves could also be included to take advantage of their ability to concentrate contaminants. Automated equipment could be used to sample water and sediment at selected intervals. An example of an integrated sampler is shown in Figure 4 and could be adapted for both sediment and water column assessments of marine and freshwater environments. The benthic flux portion of the integrated sampler (without animals) has already been used at the Puget Sound Naval Shipyard, and NOAA plans to use this device in conjunction with transplanted mussels and clams in a San Diego Bay study to evaluate bivalve bioindicators.

CONCLUSION

Regional monitoring programs in Puget Sound would be enhanced with measurements of bioaccumulation and bioeffects in resident and transplanted bivalves. Transplants in particular offer an experimental approach to monitoring that combines the experimental control of laboratory bioassays with the environmental realism of field monitoring. A scenario has been presented for using an ERD triad that has a number of applications for combining monitoring and research, and combining various monitoring programs that already exist. Monitoring bioaccumulation and bioeffects provides a direct, *in situ* evaluation that cannot be obtained even with a combination of discrete chemical measurements of water or sediment samples, laboratory bioassays, and benthic community analyses.

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PUGET SOUND RESEARCH '95

SESSION 3C

HARMFUL ALGAE: LIVING RESOURCES AND PHYSICAL PROCESS

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HARMFUL PHYTOPLANKTON IN PACIFIC NORTHWEST WATERS

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INTRODUCTION

Phytoplankton in the sea are usually thought to be beneficial because they often make up the base of the marine food web. However, a few dozen of the more than 10,000 known phytoplankton species produce blooms that may be harmful to other marine organisms and to humans. The toxins produced by these algae are among the most potent non-protein toxins known and may be lethal in nanogram to microgram amounts. The toxins affect membrane permeability and ion transport. They accumulate in filter-feeders, usually bivalve molluscs, which then act as vectors in the food chain. The toxins give no indication of their presence and they cannot be destroyed by cooking or freezing. There are no specific antidotes.

While the problem of harmful algal blooms (HABs) has been known for hundreds of years, the concern now is that these blooms are increasing in frequency, severity, and duration on both local and global scales. Further, the harmful species belong to a variety of morphologically and physiologically diverse algal groups, and the number of species known to produce toxins is increasing. Possible reasons for the apparent spread include 1) eutrophication of coastal waters by human activities that may lead to proliferation of harmful species; 2) unusual climatological conditions such as El Niño events; 3) increased use of coastal areas for aquaculture operations that may enrich local waters and stimulate algal growth or simply reveal harmful species that were present, but previously undetected; 4) transport of resistant cysts or spores in ships' ballast water; and 5) increased awareness of harmful species.

In the Pacific Northwest, there are three main public health and economic problems related to harmful algae: paralytic shellfish poisoning (PSP), domoic acid poisoning (DAP), and mortalities of pen-reared salmonids. In the case of PSP and DAP, potent toxins are produced that find their way through the food chain to humans, where they cause gastrointestinal and neurological problems. Salmonids at aquaculture sites may be killed by phytoplankton species that damage or clog fish gills but are not toxic to humans. Still other phytoplankton species produce harmless water discolorations, but the decay of these dense blooms may kill fish, shellfish, and other invertebrates by oxygen depletion.

A term almost synonymous with harmful algae is red tide. It is frequently used to describe discolored water, and many people immediately associate it with toxin production. In the Pacific Northwest, this is usually PSP. However, the most spectacular red tides here usually are produced by organisms that are harmless, while the harmful species often produce toxins at cell concentrations that are not visible to the eye and so do not produce discolored water. Further, some blooms, including toxic ones, may be subsurface and not seen.

ORGANISMS AND THEIR TOXINS

Paralytic Shellfish Poisoning (PSP)

The Pacific Northwest has a long history of HAB problems, with PSP being the best known. What is probably the first recorded death from PSP occurred in 1793 when several of Captain Vancouver's crew became ill and one died after eating blue mussels for breakfast. The description of the incident in Vancouver's log (quoted in Quayle, 1969) leaves little doubt that this was a PSP incident. In 1799, more than 100 Aleut Indians, working for the Russian fur trader Alexander Baranof, died, apparently from PSP, after eating mussels at what is now called Peril Strait near Sitka, Alaska (Quayle, 1969).

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No further cases were recorded in the area until 1942, when three people on Vancouver Island and three in Washington died after eating clams and mussels. At that time, the Washington Department of Health imposed a closure for the harvest of all bivalves for the coastal area from Dungeness Spit to the Columbia River from April 1–October 31; this closure is renewed every year. A causative organism was not linked to an illness or fatality here until 1965 (Prakash and Taylor, 1966), but it is now known that PSP is caused by species of the dinoflagellate genus *Alexandrium* (previously called *Gonyaulax* and *Protogonyaulax*).

No illnesses were reported from consuming shellfish harvested in Puget Sound before 1978, although low levels of PSP toxin were present in some shellfish samples. In September 1978, however, widespread toxicity occurred starting in Whidbey Basin and extending south to Des Moines. Toxin levels of 30,000 μg/100 g of shellfish meat in mussels (*Mytilus edulis*) were among the highest ever reported at that time. Now, PSP has been detected in shellfish from Carr Inlet (1988), Case Inlet (1991), and Seabeck on Hood Canal (1991), and many areas throughout western Washington are closed for recreational and commercial shellfish harvesting for various periods during the year.

Clams, mussels, oysters and other bivalves are usually thought to be the carriers (vectors) for PSP to humans, but this is not always the case. In Puget Sound and elsewhere, carnivorous gastropods, including moonsnails, whelks, and other snails, may contain high levels of PSP (Matter, 1994 and this volume). Crabs, including kelp (*Pugettia producta*) and red rock (*Cancer productus*) crabs from Puget Sound and Dungeness (*Cancer magister*) and Tanner (*Chionocetes* spp.) crabs in Alaska may also contain PSP toxins (Matter, 1994 and this volume).

PSP toxins, i.e., saxitoxins, occur as a suite of 12 water-soluble compounds that bind to sodium channels and block the flow of sodium ions into cells. However, metabolic changes may occur in the shellfish so that at least 18 different toxins may be present. The actual toxin composition in the shellfish depends on that in the dinoflagellates at a particular site, possible selective uptake and storage of the toxins, and changes in composition due to metabolic activity in the shellfish tissues (Shumway, 1990). In humans, symptoms include tingling or numbness around the mouth, headache, vomiting, and diarrhea; in extreme cases, there may be muscle paralysis and respiratory difficulty. The worldwide regulatory closure level for PSP is 80 μg/100 g of shellfish meat.

Domoic Acid Poisoning (DAP)

In the fall of 1991, a new toxin, domoic acid, appeared in West Coast waters. Discovered in mussels commercially harvested in eastern Canada in 1987, the source of this toxin was traced to the diatom *Pseudonitzschia pungens* f. *multiseries*. This was the first time that diatoms were found to produce toxins. At the present time, at least four species of this genus are known producers (i.e., *P. pungens* f. *multiseries*, *P. pseudodelicatissima*, *P. australis*, and *P. seriata*).

On the West Coast, domoic acid first occurred in Monterey Bay, Calif., when deaths of pelicans and cormorants were traced to their food source, anchovies, that were feeding on phytoplankton dominated by *Pseudonitzschia australis* (Fritz et al., 1992; Work et al., 1993). Domoic acid, with toxin levels ranging from ca. 1 μg/g wet weight in oysters to 2300 μg/g in anchovies, has been found in a variety of marine invertebrates from the California coast, including Dungeness, rock, and stone crabs, razor clams, California mussels, oysters, and spiny lobsters (California Department of Health Services, 1992).

By late October 1991, domoic acid was found in intertidal razor clams on the Oregon and Washington coasts, and both recreational and commercial harvests were closed. Other bivalves, including commercially grown oysters, mussels, and other clams, were tested and did not contain the toxin. Domoic acid was found in the viscera of Dungeness crabs, and their commercial harvest was closed for a short time in late 1991 and early 1992. Since 1991, the spring and fall harvests of razor clams have been affected either by the presence of domoic acid, or, in 1992, by the presence of PSP. A causative organism(s) for domoic acid is still (early 1995) not known for certain for Washington waters, although at least three of the four *Pseudonitzschia* species known to produce domoic acid in other areas are found here (Horner and Postel, 1993; R. Horner, unpubl. obs.).

Domoic acid, first isolated from the red alga *Chondria armata* in Japan, is a water-soluble, neuroexcitatory amino acid that binds to specific sites on nerve cells in the brain causing the cells to fire repeatedly until they die. As a result, one of the symptoms of this toxin is permanent, short-term memory loss; another name for the syndrome is Amnesic Shellfish Poisoning (ASP); other, less severe symptoms include nausea, vomiting, diarrhea, abdominal cramps, headache, loss of balance, and disorientation. The federal regulatory closure level for domoic acid is 20 µg/g of shellfish meat, but Washington state currently uses 15 µg/g as the action level.

Salmonid Mortalities

Heterosigma carterae

Massive blooms of this small raphidophyte flagellate, previously called *H. akashiwo* or sometimes *Olisthodiscus luteus*, frequently occur in inland waters of Washington and British Columbia and also in B.C. coastal embayments. Mortalities of pen-reared fish, especially salmon, occur most years in British Columbia and less frequently in Washington. No specific toxin has been identified, but Yang et al. (1993) believe that superoxide radicals and hydrogen peroxide formed during late-growth to stationary-growth phase may be the killing agents because fish can be protected with the addition of superoxide dismutase and catalase.

Chaetoceros concavicornis, *C. convolutus*, and perhaps *C. danicus*

These diatoms occur in low concentrations in Puget Sound and usually do not form blooms; no toxin is produced. Instead, the cells have heavy, long setae covered with short secondary spines that apparently get between the secondary lamellae of the fish gills and cause blood hypoxia because of mucus production or gill damage (Rensel, 1993, this volume).

Other Known Bloom Producers

Ceratium fusus/Gymnodinium sanguineum

These dinoflagellates have been linked to mortality of oyster larvae and adults (*Crassostrea gigas*) (Cardwell et al., 1977, 1979) and spot prawns (*Pandalus platyceros*) (Rensel and Prentice, 1980) in southern Puget Sound. There is no indication of a chemical toxin, but mortality occurs when the dinoflagellates are present and may be due to mechanical means or oxygen stress when the blooms decay. These species often occur as blooms, especially in the shallow inlets in southern Puget Sound, where concentrations may reach $>10^9$ cells/liter.

Noctiluca scintillans

This predatory dinoflagellate often occurs as spectacular, rusty red (tomato soup) patches throughout the area. When present in large concentrations, it may produce ammonia that could be detrimental to fish, but this has not been reported in the Pacific Northwest. The cells are relatively large and may be seen with the unaided eye.

Gonyaulax spinifera

Another dinoflagellate, this species formed a rusty-colored bloom covering some 500 km^2 from Grays Harbor to Barkley Sound on the open coast in August-September 1990. Large patches drifted with the tides and currents throughout the Strait of Georgia, and Haro, Rosario, and Juan de Fuca straits. There were no reports of farmed fish deaths, but oysters, clams, mussels, crabs, snails, and other invertebrates died in Barkley Sound, apparently from oxygen depletion as the bloom decomposed (Taylor and Horner, 1994).

Mesodinium rubrum

This ciliated protozoan contains algal chloroplasts and often appears burgundy red in color. It is a frequent summer bloom producer. Shellfish meat or liquor may be pink if blooms of this organism occur in areas where filter-feeding shellfish grow. The shellfish meat is not toxic.

Ceratium* spp. and *Prorocentrum micans

During the fall 1994 razor clam season on the Washington coast, clams were reported to be pink. At the same time, large streaks and patches of red water were found along the open coast. Microscopical examination of water samples indicated that the causative species were dinoflagellates of the genera *Ceratium* and *Prorocentrum*. The dinoflagellates also occurred in oyster growing areas inside Willapa Bay and some oysters were pink. There were no reports of human illnesses from eating pink razor clams, and these dinoflagellates are not known to produce toxins.

Potential Harmful Species

Other species that may cause fish kills or other harmful effects elsewhere in the world are sometimes present in Puget Sound, but are not problems here yet. Of these, four species of the dinoflagellate genus *Dinophysis*, which produce okadaic acid and diarrhetic shellfish poisoning (DSP) in Japan and northern Europe, are present here and could lead to the recognition of DSP. As few as 200 cells/liter can cause DSP, and blooms are usually subsurface. DSP symptoms—vomiting and diarrhea—are non-specific, and victims recover within a few days without treatment.

Some members of the flagellate class Prymnesiophyceae, including *Chrysochromulina polylepis* and *Phaeocystis* sp., may occur in local waters, but their occurrences and distributions are not known. The silicoflagellate *Dictyocha speculum* may have been responsible for fish kills in Denmark and France, but there is no evidence that it is a problem here. The alga, with or without a characteristic siliceous skeleton, has been found in relatively large numbers in southern Puget Sound.

CAUSES OF BLOOMS

Blooms are caused not just by the rapid growth of cells, but also by the concentration of cells at physical barriers in the sea such as fronts, coastal currents, buoyant plumes, and upwelling areas. Vertical stability of the water column is also needed. Algae can quickly remove nutrients from the warmer, less dense surface layer, leaving an adequate nutrient supply only below the pycnocline. However, motile species, such as dinoflagellates and *Heterosigma*, are able to swim and migrate to the nutrient-rich subsurface layers, where they take up nutrients at night, returning to the surface during the day to use the nutrients in photosynthesis. Moreover, blooms may become entrained in coastal currents and be carried long distances. *Gymnodinum breve*, for example, was transported as a bloom from the southwest coast of Florida, around south Florida, and up the east coast to North Carolina in 1987-88 (Tester et al., 1991).

Unusual weather conditions may also transport harmful cells to new areas where they can become established and cause blooms. For example, in the fall of 1972, Hurricane Carrie apparently transported *Alexandrium* cysts from the Bay of Fundy to New England. Now, shellfish toxicity occurs every year in the area from Maine to Massachusetts. Further, some, but not all, PSP events in the Pacific Northwest can be correlated with El Niño years (Erickson and Nishitani, 1985), while heavy rainfall and high river runoff have been implicated in the apparent spread of PSP into Puget Sound in 1978.

In many areas, environmental changes due to human activity are often blamed for the occurrence of harmful algal blooms. Increased domestic, agricultural, and industrial wastes add nutrients to the water that may stimulate algal blooms. Changes in nutrient ratios, e.g., N:Si, may favor blooms of nuisance or harmful species over natural blooms of diatoms in the spring and fall. At the present time, however, none of the bloom episodes in Pacific Northwest waters can be directly linked to pollution effects (Taylor and Horner 1994).

Other human activities that may lead to more harmful algal blooms include increased aquaculture operations. This does not necessarily mean that the aquaculture sites are causing eutrophication. Instead, mortalities at a fish farm, for example, may indicate an alga that always has been present as part of the so-called "hidden flora," but was not noticed until fish died. Harmful algal species may also be imported with aquaculture products. The brown seaweed *Sargassum muticum*, for instance, was probably brought to Washington with Japanese oyster spat in the 1930s. Ballast water and sediment in ballast tanks are other ways harmful species and/or their cysts can be transported from place to place (Hallegraeff, 1993).

ECONOMIC LOSSES

We are just beginning to realize the economic impacts of harmful algal blooms. The blooms can have adverse effects on the viability, growth, reproduction and recruitment of marine populations. The toxins can move through ecosystems. For example, deaths of humpback whales on the U.S. east coast in 1987 were traced to PSP toxins concentrated in the livers and kidneys of mackerel eaten by the whales. The toxins presumably came from zooplankton and small fish eaten by the mackerel (Anderson, 1994).

There may be ripple effects. During the domoic acid incident on the Washington coast in 1991, oysters and other clams were never toxic, but consumers thought they might be, and sales plummeted. Economic losses may also be felt in lower product prices, lost jobs, and bankruptcies. There may be less investment in aquaculture operations, and marine recreational opportunities may be lost through closed harvest seasons.

FUTURE

Despite the heavy use of marine resources from Pacific Northwest waters for both recreational and commercial consumption, few health-related problems have occurred. This may be due partly to under-reporting because symptoms in mild cases are often ignored or self-treated. However, the main reason is the cautious and proactive approach taken by public health agencies to educate the public and regulate the harvest of shellfish and the aquaculture industry. Unfortunately, current monitoring and regulatory programs may not be adequate when new outbreaks occur, and response to a new problem may be slow and uncoordinated, as it was in 1991 when domoic acid first occurred in razor clams. Moreover, most of our information comes from toxin levels in shellfish, not from knowledge about the biology of the causative organisms.

There are several species of phytoplankton linked to HABs that regularly occur in Pacific Northwest waters now, and we can assume that more harmful species and their effects will be discovered in the future. Modest efforts are continuing to extend our knowledge of their distribution in time and space throughout the area, but currently there is no consensus among scientists, federal and state agencies, the aquaculture industry, and the public that HABs are a big problem or even a priority for further research. Thus it seems that future work here will continue only in response to some major crisis or because of the personal interest and persistence of individuals with the patience to wait for long-term information to accumulate.

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ACCUMULATION OF PARALYTIC SHELLFISH POISONING TOXINS IN THE MARINE FOOD WEB

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INTRODUCTION

Biotoxins produced by marine phytoplankton accumulate in marine organisms such as filter-feeding bivalve molluscs, planktivorous fish, and higher food web predators. Paralytic shellfish poisoning (PSP) is a potentially life-threatening syndrome caused by ingestion of marine organisms containing phytoplankton biotoxins. The biotoxins responsible for PSP are composed of a lethal complex of neurotoxins, the most potent of which is saxitoxin (STX). In Washington state, PSP toxins are produced by the dinoflagellate *Alexandrium catenella.*

After filter-feeding bivalve molluscs consume toxic dinoflagellates, PSP toxins accumulate in the tissue of the bivalves. Predatory snails such as moonsnails and whelks have no filter-feeding capacity and presumably obtain PSP toxins from their filter-feeding prey, i.e., clams and other bivalves. They consume bivalves by either prying open the shell or boring a hole through the shell, accumulating PSP toxins in their digestive gland (Caddy and Chandler, 1968; Medcof et al., 1966). High PSP toxin levels have been observed in whelks when filter-feeders in the same vicinity were most toxic (Medcof, 1972).

Recreational harvesters have traditionally gathered shellfish from Puget Sound beaches, and many commercial shellfish operations exist in the area. The monitoring program conducted by Washington Department of Health (WDH) protects both groups of consumers by issuing harvesting advisories when PSP toxin levels meet or exceed 80 mg saxitoxin (STX) equivalent per 100 g shellfish tissue.

Vectors of PSP Toxins

Animals in the marine food web that accumulate PSP toxins from dinoflagellates include zooplankton, fish larvae, marine invertebrates, fish, birds, and mammals (see Matter, 1994). Figure 1 illustrates documented routes of PSP toxin transfer. While the most common vectors transmitting PSP toxins to humans are filter-feeding bivalve molluscs, additional marine food web vectors that affect humans include predatory snails and finfish.

The species of marine invertebrates that have tested positive for PSP toxins and are found in Puget Sound include barnacles (*Balanus* spp.), dogwinkles (*Nucella lamellosa* and *Nucella lima*), hermit crabs (*Pagurus* spp.), kelp crabs (*Pugettia producta*), moonsnails (*Polinices lewisii*), Pacific falsejingles (*Pododesmus cepio*), periwinkles (*Littorina sitkana*), red rock crabs (*Cancer productus*), shore crabs (*Hemigrapsus nudus*), and tritons (*Fusitriton* sp.). Of these species, accumulation of PSP toxins is best documented in predatory marine snails, e.g., moonsnails and dogwinkles (see Matter, 1994).

Recreational Harvesting

While bivalve molluscs are well-monitored for PSP toxins by state health departments, Washington state does not directly measure toxin levels in predatory snails. However, WDH began including them in harvesting advisories during the spring of 1994. Warnings advise recreational shellfish harvesters against collecting the predators of bivalve molluscs, such as moonsnails, from beaches with shellfish harvesting advisories. Unlike shellfish, finfish appear unable to accumulate PSP toxins in their muscle tissue (White, 1981; White, 1984). On the basis of this evidence, human risk from the consumption of fish containing PSP toxins may primarily involve the viscera.

Moonsnails and whelks have tested positive for PSP toxins and are recreationally harvested and eaten on the Atlantic and Pacific coasts (Matter, 1994). In Canada, the digestive gland of whelks is usually

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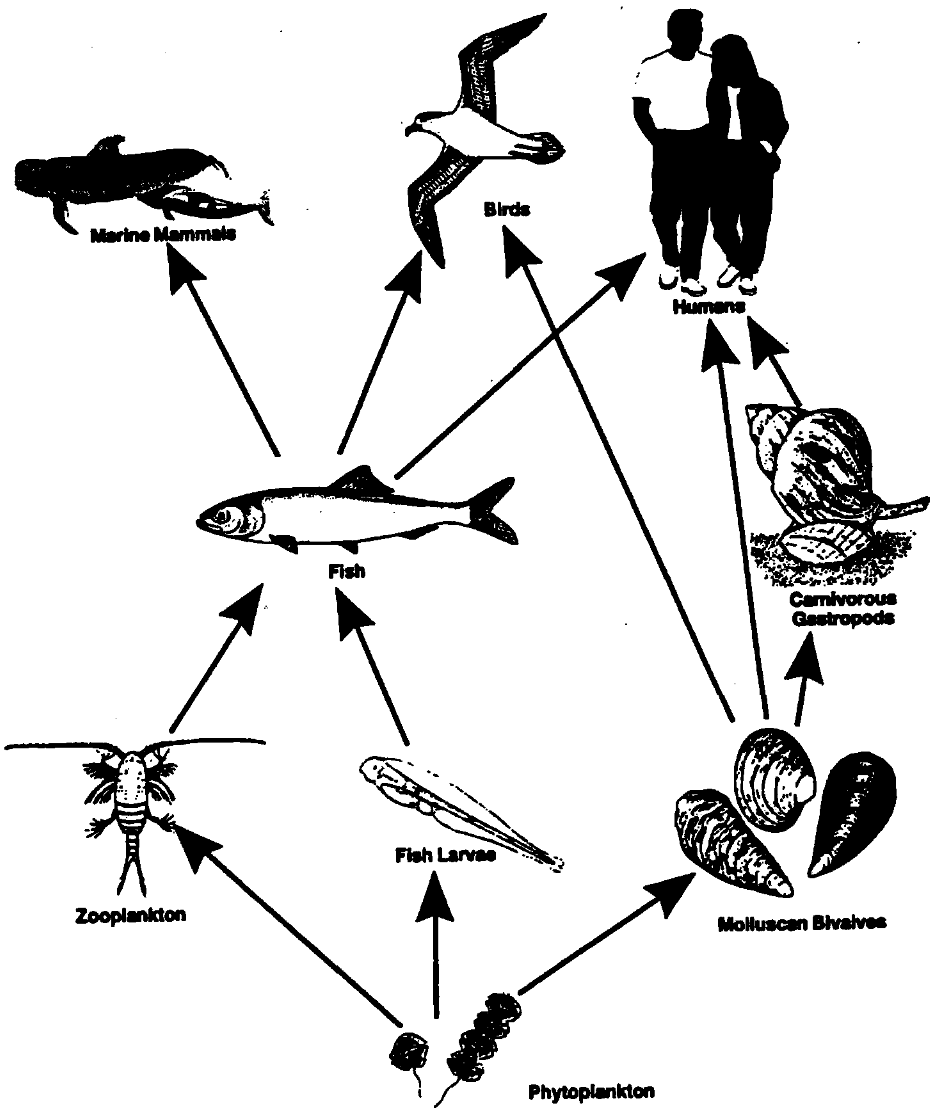

Figure 1. Documented routes of paralytic shellfish poisoning toxin transfer through the marine food web

trimmed during commercial processing. However, recreationally harvested whelks are usually boiled whole, and parts of the digestive gland are often eaten (Medcof, 1972). Moreover, boiling whole whelks or moonsnails may allow toxins located in the digestive gland to leach into the water, then into other tissues.

Recreational harvesters have traditionally gathered and consumed clams, mussels and oysters from Puget Sound beaches. In addition to bivalve molluscs, Washington state Native Americans eat chitons, gooseneck barnacles, limpets, moonsnails, sea cucumbers, sea urchins and whelks. Asian-Americans appear to be the major consumers of recreationally harvested intertidal marine snails and other non-bivalve marine invertebrates from Puget Sound public beaches. While most Native Americans are familiar with the

dangers associated with harvesting shellfish from Puget Sound, many Asian-Americans are not familiar with PSP (see Matter, 1994).

Results of a detailed study of the collection of non-game marine invertebrates (those species not classified as food fish, shellfish or game) in Puget Sound by Carney and Kvitek (1991) concluded that more than 50 percent of collectors are Asian-American, and approximately 30 percent of the species collected are eaten. Species most often collected for food are moonsnails (*P. lewisii*), graceful crabs (*Cancer gracilis*) and dogwinkles (*Nucella* spp.). A smaller study interviewed students from English as a Second Language (ESL) classes (Matter, 1994). More than 90 percent of ESL students who harvested invertebrates from Puget Sound beaches for food were Asian-American. Shellfish harvested for consumption other than bivalve molluscs included limpets, moonsnails and other predatory snails.

Over the past several years there has been a large influx of Asian-American immigrants and refugees to the Puget Sound area. Changes in the ethnic composition of recreational harvesters and the accompanying changes in species being harvested for food from Puget Sound may increase the risk of PSP to the exposed population. In order to educate the public about safe shellfish harvesting practices, the Washington Department of Social and Health Services has initiated a cultural outreach program unique to Washington state.

Predatory Snails

PSP toxins have been detected in many field-collected predatory snails. Bond (1975) reported PSP toxins in whelks (*Buccinum undatum*, *Colus stimpsoni* and *Neptunea decemcostota*), northern moonsnails (*Lunatia heros*, now *Euspira heros*), dogwinkles (*Nucella lapillus*) from the east coast of Canada, and moonsnails (*Polynices lewisii*, now *E. heros*) from the west coast of Canada. Tufts (1979) reported PSP toxins in dogwinkles and moonsnails along the Atlantic coast of the United States. White et al. (1993) reported low levels of PSP toxins in Atlantic slippersnails (*Crepidula fornicata*) and levels greater than 2000 mg STX per 100 g tissue (whole individuals) in Northern moonsnails (*E. heros*) from the Gulf of Maine. Sasner et al. (1975) reported levels greater than 1300 mg STX equivalent per 100 g tissue in moonsnails (*E. heros*) from Massachusetts. MacDonald (1970) reported the presence of PSP toxins in dogwinkles (*Thais lamellosa* and *T. lima*, now *Nucella lamellosa* and *N. lima*) from the Strait of Juan de Fuca.

The consumption of recreationally harvested predatory snails has resulted in PSP illnesses and death on several occasions. In Quebec, 12 cases of PSP illness in 1936 and three illnesses and one death in 1970 confirmed the dangers of eating whelks (Medcof et al., 1966; Medcof, 1972). Two cases of PSP illnesses were reported from the consumption of northern moonsnails (*Polynices heros*, now *E. heros*) in Massachusetts during 1975 (Tufts et al., 1975). In 1984, consumption of the snail *Oliva vidua fulminans* resulted in five deaths and three hospitalizations from PSP in Malaysia (Kan et al., 1986; Sang and Ming, 1984). Malaysian researchers have also detected PSP toxins in the conch *Lambis* (Sang and Ming, 1984), and other gastropods (Jaffar and Subramaniam, 1984). In Argentina, a PSP illness was suspected from consumption of the marine snail *Zidona angulata* since viscera from these snails contained high levels of PSP toxins (Elbusto et al., 1991).

Predatory snails appear to depurate PSP toxins slowly. MacDonald (1970) suggested long-term PSP toxin storage in the file dogwinkle (*N. lima*) during a 13-week study in the Strait of Juan de Fuca. The northern moonsnail (*E. heros*) exhibited slow depuration of PSP toxins during a four-year field study in the Gulf of St. Lawrence, Canada (Worms et al., 1993). During 1988 (the first year of the study), significant PSP toxin levels were measured in bivalves, but none were detected in northern moonsnails. PSP toxin levels in bivalves decreased to much lower levels over the following three years, while the mean level in northern moonsnails increased to 154 mg STX equivalent per 100 g moonsnail tissue in 1989, decreasing to mean levels of 94 in 1990 and 82 in 1991. Slow depuration of PSP toxins in predatory snails has also been recognized by others (see Matter, 1994; White et al., 1993).

Other Marine Invertebrates

Marine invertebrates other than filter-feeding bivalve molluscs and predatory snails that are able to accumulate PSP toxins include periwinkles, Pacific falsejingles, tunicates, lobsters, barnacles and crabs (Foxall et al., 1979; Jonas-Davies and Liston, 1985; MacDonald, 1970; Matter, 1994; Quayle, 1969; Shumway, 1995). MacDonald (1970) detected PSP toxin levels in periwinkles (*Littorina sitkana*), hermit crabs (*Pagurus* spp.), and shore crabs (*Hemigrapsus nudus*) from the Strait of Juan de Fuca. In California, PSP toxin levels of 59 and 170 mg STX equivalent per 100 g shellfish tissue were detected in the Pacific falsejingle (*Pododesmus cepio*) (see Matter, 1994). Two people reported PSP symptoms after eating filter-feeding tunicates (*Holocynthia roretzi*) in Japan. The mantle of the tunicate, which is the main edible portion, had significant levels of toxicity (over four times the closure level) (Nagashima et al., 1984). Lobsters (*Homarus americanus*) accumulate PSP toxins in the hepatopancreas after consuming toxic scallops. Levels greater than 1600 mg STX equivalent per 100 g tissue were detected in lobster hepatopancreas during field studies in the Gulf of Maine and Bay of Gaspe. Lobster hepatopancreas, also known as tomalley, is considered a delicacy (see Shumway, 1995). Furthermore, since lobsters are traditionally boiled whole, leaching of PSP toxins into other tissues may pose a problem.

Filter-feeding barnacles tested positive for PSP toxins in several locations. In British Columbia, Quayle (1969) reported 51 mg STX equivalent per 100 g barnacle tissue (*Balanus cariosus*). In Puget Sound, Jonas-Davies and Liston (1985) reported levels from 19 to 84 mg STX equivalent per 100 g barnacle tissue (*Balanus* spp.). In Maine, barnacles (unknown spp.) tested positive for PSP toxins when other shellfish were toxic (see Matter, 1994).

PSP toxin levels ranging from 23 to 1170 mg STX equivalent per 100 g tissue were detected in the viscera of kelp crabs (*Pugettia producta*) and from 15 to 285 in red rock crabs (*Cancer productus*) collected from intertidal areas of Puget Sound. However, muscle tissue levels were undetectable to low (Jonas-Davies and Liston, 1985). PSP toxin levels as high as 800 in the viscera of Dungeness crabs (*Cancer magister*) and Tanner crabs (*Chionoecetes bairdi* and *Ch. opilio*) from Alaska have periodically restricted their harvest since 1990 (see Matter, 1994). Furthermore, a laboratory feeding study found significant levels of PSP toxins in the digestive gland of New England rock crabs (*Cancer irroratus*) and lower levels in other tissues after consumption of highly toxic bivalves (Foxall et al., 1979).

Most marine organisms that accumulate PSP toxins obtain them from the motile cells of *Alexandrium* or by ingesting toxic prey such as bivalves. However, when motile cells encyst, they become non-motile and sink to the bottom, where they may be ingested by non-predatory, non-filter-feeding benthic invertebrates. PSP toxins were detected in ormers (*Haliotis tuberculata*), a browsing gastropod from northwest Spain. Unlike predatory gastropods tested for PSP toxins, the largest quantity of STX was present in the foot of the ormer. Since no other PSP toxin-producing organisms were detected in the phytobenthos or in the gastric contents of the ormers, the toxicity could have been due to ingestion of cysts from the sediment (Martinez et al., 1993). STX also was detected in the green turban shell (*Turbo marmorata*), a herbivorous snail that feeds on algae and detritus (Yasumoto and Kotaki, 1977).

Finfish

Human PSP illnesses and deaths from consumption of contaminated finfish were reported in Malaysia during a PSP toxin-producing phytoplankton bloom (Adnan, 1984; Jaafar and Subramaniam, 1984). Laboratory studies have shown that herbivorous zooplankton and fish larvae transmit PSP toxins to planktivorous fish (Yazdandoust, 1985; Erickson, 1988; White et al., 1989).

Finfish mortality has been attributed to PSP contamination on several occasions. Mass mortality of Atlantic herring in the Bay of Fundy was attributed to the consumption of pteropods that had grazed on PSP toxin-producing phytoplankton (White, 1977). During a very large PSP toxin-producing phytoplankton bloom in the Faroe Islands, Denmark, dead flatfish (mostly flounder) washed up on the sand, and local fishermen were unable to catch any fish in the fjord during the weeks after the bloom (Mortensen, 1985). In addition, researchers from other locations have reported positive analysis of STX in fish during PSP

toxin-producing phytoplankton blooms, without mention of trophic relationships (De Silva et al., 1989; Hwang et al., 1990; Jaafar and Subramaniam, 1984; Jaafar et al., 1989; Ming and Wong, 1989; Oshima, 1989). These examples indicate that fish may be important vectors for the transfer of PSP toxins from lower to higher trophic levels of the marine food web.

SUMMARY AND CONCLUSIONS

Among invertebrate vectors of PSP toxins, filter-feeding bivalve molluscs pose the most serious public health threat to recreational harvesters in Puget Sound due to the numbers harvested. However, as shown above, the list of potential other vectors is long. While fewer predatory snails are harvested than bivalves, the threat from recreationally harvested predatory snails should not be ignored. WDH has acknowledged the dangers associated with eating predatory snails such as moonsnails by including them in shellfish harvesting advisories. It is readily apparent that health departments cannot continually monitor for PSP toxins in all species that may potentially be harvested from all beaches. However, it would be judicious for Puget Sound researchers to quantify toxin levels and study depuration rates of recreationally harvested invertebrates that accumulate PSP toxins—such as barnacles, dogwinkles, moonsnails and periwinkles—that are not included in the WDH shellfish monitoring program

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WASHINGTON STATE BIOTOXIN MONITORING PROGRAM

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ABSTRACT

The Washington Department of Health began routine testing of shellfish for paralytic shellfish poisoning (PSP) in the 1940s and for domoic acid in the fall of 1991. Shellfish from all commercial growing areas and most recreational beaches are tested for biotoxins at the state's Public Health Laboratory. Samples from commercial areas are submitted by the commercial shellfish operations. Volunteers and local county health districts provide samples from recreational beaches. Shellfish harvesting is closed when levels equal or exceed 80 micrograms per 100 grams shellfish for PSP and 15 parts per million for domoic acid.

Most areas are tested routinely at two-week intervals from April through October. Some areas are tested year-round and/or weekly during the summer and fall, when biotoxin levels in shellfish are more likely to increase to unsafe levels. Currently more than 3,000 shellfish samples are tested for biotoxins each year in Washington state. The Department of Health also coordinates an early warning program using caged mussels at more than 30 sites throughout Puget Sound and coastal areas. In addition the state plans to expand a phytoplankton monitoring program begun in 1992.

Commercial growers are notified directly by the state when shellfish harvest is prohibited because of biotoxins. Local health districts may post recreational beaches and notify the news media when recreational closures are in effect. Information on closures is also provided by the state Department of Health on a toll-free Biotoxin Hotline recording, which is updated immediately whenever changes in closures occur. Although unsafe levels of biotoxins have required closures in all but the lower portions of Hood Canal and South Puget Sound, only one outbreak of five cases of PSP involving commercial product and a small number of isolated cases involving recreational shellfish have been reported in Washington since the monitoring program began more than 50 years ago.

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DECADAL COVARIATIONS OF SEQUIM BAY PARALYTIC SHELLFISH POISONING (PSP) WITH SELECTED PACIFIC NORTHWEST ENVIRONMENTAL PARAMETERS

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INTRODUCTION

A number of parameters describing the Pacific Northwest environment vary at decadal intervals of approximately 20 years (Ebbesmeyer et al., 1989; Ebbesmeyer et al., 1991; see Figure 1 for locations). Here we explore the concept that concentrations of paralytic shellfish poison (PSP) toxins also covary with selected environmental parameters at a decadal period. To do this we compare PSP toxin concentrations in Sequim Bay butter clams (*Saxidomus giganteus* Deshayes, 1839) with five parameters describing physical and biological aspects of the U.S. Pacific Northwest environment.

The basis for this possible linkage lies in the changes in the composition of the phytoplankton that shellfish filter out of the water. During periods of favorable conditions, *Alexandrium catenella* (Whedon and Kofoid), a dinoflagellate that produces PSP toxin, can undergo rapid population increases resulting in a "bloom." Thus, PSP toxin concentrations in shellfish can be used as an indicator of bloom intensity, although blooms or high concentrations of the dinoflagellates are not needed for shellfish to be toxic.

Little available detailed information is available about environmental cues that initiate, sustain or terminate algal blooms in Pacific Northwest waters, but we are reasonably certain that these blooms, including those of *A. catenella*, are influenced by water temperature, nutrient concentrations, pycnocline stability, wind conditions and runoff (Nishitani et al., 1989). Additional investigation indicates that PSP events may be greater in intensity in the Pacific Northwest during very strong El Niño/Southern Oscillation events (Erickson and Nishitani, 1985).

Several considerations led to our selection of the parameters described in this paper. We sought to understand the linkages between physical and biological parameters over as long a time frame as possible. Because many environmental parameters covary at the decadal time-scale, we restricted our examination to those for which long time series are available. Physical parameters were chosen that are considered to have large-scale effects on the environment and are likely to have implications for biological systems, including the growth of algal populations like those of *A. catenella*. These parameters include the movement of subarctic surface water in the North Pacific Ocean as well as air temperature, precipitation and snow pack at selected locations in the Pacific Northwest (PNW Index, or PNI; see Figure 1 for locations). In addition, biological parameters were considered that might be affected by the same large-scale environmental conditions as algal blooms, including migration routes of returning Fraser River sockeye salmon (*Oncorhynchus nerka*) and the condition or "plumpness" of oysters (*Crassostrea gigas*) in Willapa Bay.

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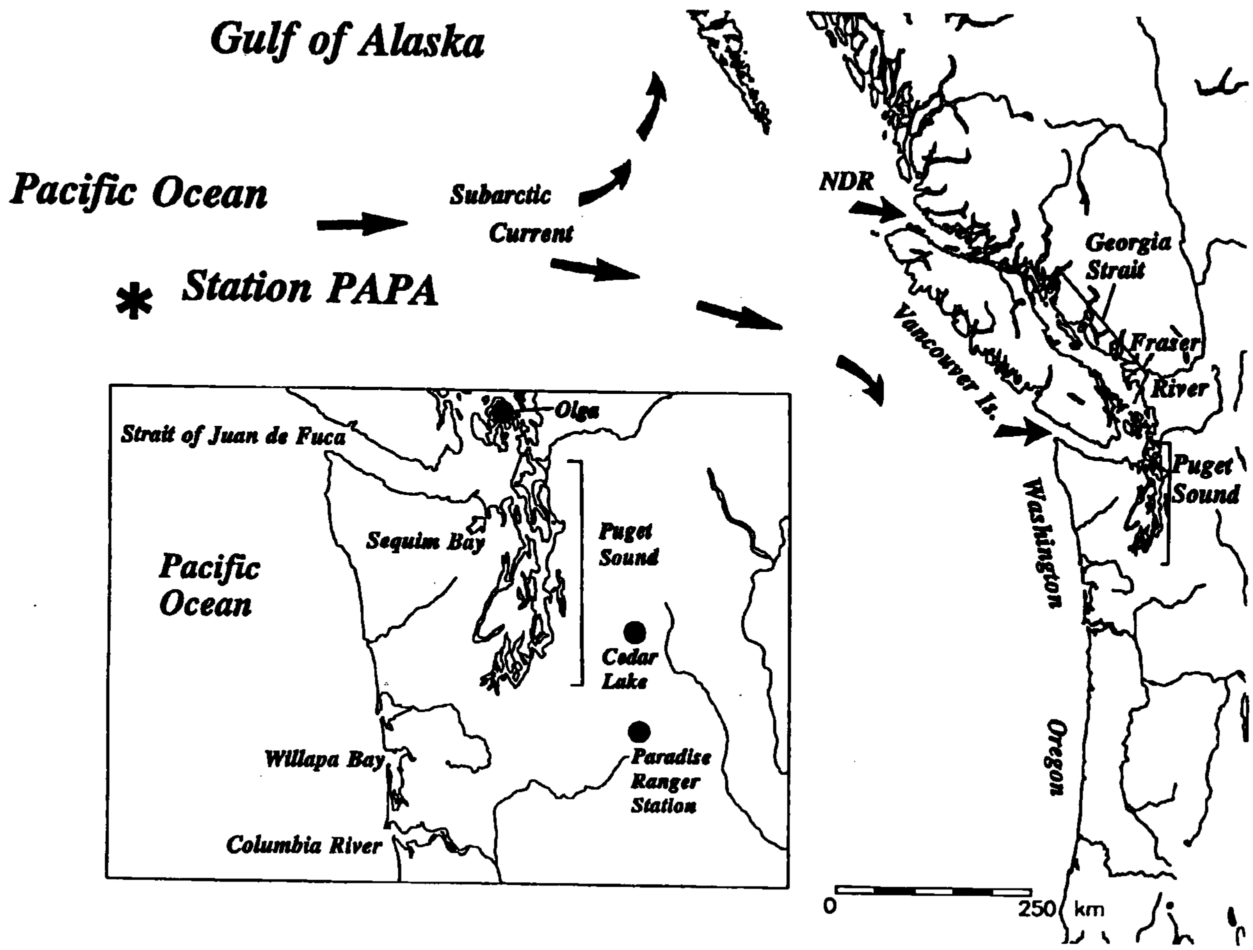

Figure 1. Locations associated with five environmental parameters. Drift of subarctic water (arrows) from Ocean Weather Station Papa (*); Pacific Northwest index (PNI) based on precipitation at Cedar Lake, snow pack depth at Paradise Ranger station, Mount Rainier, Wash., and air temperature at Olga; northern diversion rate, percentage of sockeye salmon returning to the Fraser River from the Pacific Ocean around the northern end of Vancouver Island (arrows with NDR); oyster condition index (OCI) in Willapa Bay; and maximum PSP toxin concentrations in butter clams during June to October at Sequim Bay.

The clearest relationship between the dynamics of a bloom of *A. catenella* and the associated physical environmental factors will be exhibited within a relatively confined bay. Since decadal variations typically last about 20 years, it was important to obtain PSP time-series from before 1970. The most consistent long-term records of toxicity in a single species of shellfish within a bay were those of butter clams in Sequim Bay. To examine PSP events, we determined maximum PSP toxin concentrations each year in that bay. Other indices of PSP activity, e.g., extensiveness of the area affected and intensity of blooms (based on the number of samples with high toxicity versus the number with low toxicity), are used in a regulatory context in British Columbia (Chiang, 1985), but these indices are less useful for examining bloom dynamics at a particular site.

METHOD OF STANDARD NORMAL DEVIATES

To simplify the analysis, the parameters' varying dimensions (degrees of longitude and latitude for water drift; percentage for Pacific salmon; mg of dry weight per cubic centimeter for oyster condition;

μgrams toxin/100 grams shellfish meat for PSP toxicity) were eliminated and annual standard normal deviates were used.

Three steps were applied to each variable: 1) the mean (m) and standard deviation (s) of the annual values were computed; 2) each annual value (x) was converted to a standard normal deviate (SND) by computing [(x-m)/s]; and 3) the annual SND values were smoothed, using a running five-year average, where each value in the five-year average is equally weighted, and the average is entered for the middle year of the five-year average. The SND has no dimensions because the time records are normalized by the standard deviation of the annual values. For example, the 1955 salmon diversion rate minus the long-term mean divided by the standard deviation yields a dimensionless number. In essence the SND method places the temporal fluctuations for each environmental variable on a scale between approximately -1 and +1.

ENVIRONMENTAL PARAMETERS

Five parameters were investigated (see Figure 1 for locations; Figure 2 for SND time-series).

Winter Drift from Ocean Weather Station Papa

The movement of subarctic surface water in winter (December through February 1946-94) was determined using drifter tracks for the sea surface, simulated with the Ocean Surface Current Simulations model (OSCURS; Ingraham and Miyahara, 1988). Each trajectory began at Ocean Weather Station Papa (50 degrees north latitude; 145 degrees west longitude) on 1 December of one year, and continued daily until 28 February of the following year. This station was chosen because it is located in the subarctic current, and oceano-

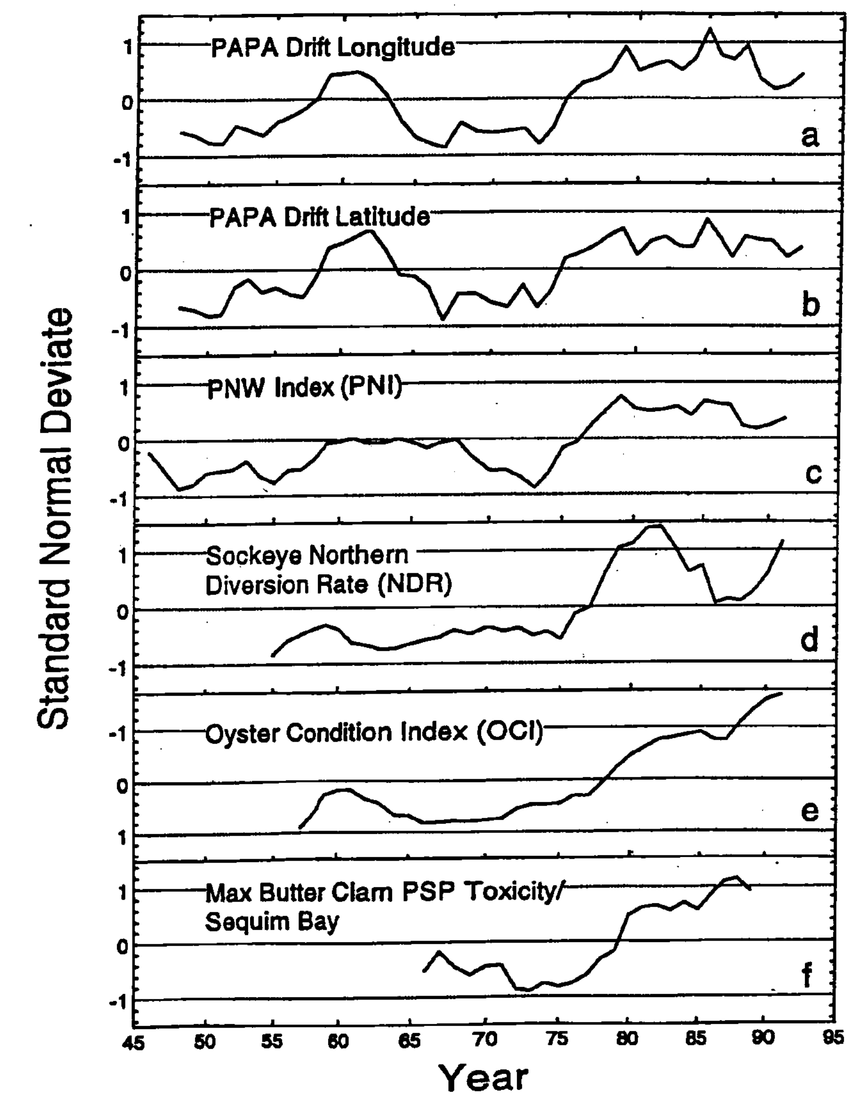

Figure 2. Decadal variations of five environmental parameters. a, b) longitude and latitude, respectively, of the simulated drift of water at the end of winter from Ocean Weather Station Papa; c) Pacific Northwest index (PNI); d) northern diversion rate (NDR); e) oyster condition index (OCI) at Willapa Bay (note that the ordinate has been reversed); and f) annual maximum PSP toxin concentration in butter clams in Sequim Bay.

graphic observations since the 1950s are available. The latitude and longitude at the end of each three-month simulation were chosen to represent the supply of subarctic water along the North American coast at the end of each winter. Changes in the direction and speed of the subarctic surface water, and thus the track followed each year, are determined mainly by winds.

Pacific Northwest Index (PNI)

This index equals the average of the SND values previously determined for three parameters that represent Pacific Northwest decadal variations during the 1900s (Ebbesmeyer et al., 1989; Ebbesmeyer and Strickland, 1995): air temperature at Olga, Wash., that reflects sea surface water temperatures; precipitation at Cedar Lake in the Cascade foothills, which supplies a major portion of Seattle's water; and snow pack depth at the Paradise Ranger Station, Mount Rainier, Wash. (see inset, Figure 1 for locations).

Northern Diversion Rate for Fraser River Sockeye Salmon (NDR)

Sockeye salmon return from the Pacific Ocean to the Fraser River around Vancouver Island through either Johnstone Strait (northern route) or Juan de Fuca Strait (southern route). The percentage of the total run returning in a given year via the northern route is referred to as the Northern Diversion Rate.

Oyster Condition Index for Willapa Bay (OCI)

The condition of oysters in Willapa Bay is expressed as the ratio of dry weight of organic matter to the volume of the oyster shell cavity (Schoener and Tufts, 1987). Years with a high oyster condition index are those in which oysters are plump, thereby bringing higher market prices. OCI values reported monthly by the Washington Department of Fish and Wildlife, Willapa Field Station, for two sites in Willapa Bay (Parcel A; Stony Point) were averaged for January through December, 1955-1993.

PSP Toxicity

Washington Department of Health data (1964-1993) for PSP toxin concentrations (micrograms toxin per 100 grams of shellfish meat) in butter clams in Sequim Bay is the longest reasonably continuous record of PSP activity in a single Pacific Northwest water body. There are two caveats to be considered in using these data. Time and station gaps make it possible that PSP values higher than the recorded maxima may have occurred. Furthermore, because butter clams tend to retain their toxins for long periods, PSP values may reflect past as well as present bloom conditions. For this analysis, we examined two parameters: (1) the annual maximum PSP toxin concentration recorded for an individual clam; and (2) the average of the maximum toxin concentrations recorded during each of three months (equally weighted values from June, July, and August), 1964-1991, when the data were most complete (only four of 84 monthly values missing). Although sampling was not conducted systematically in terms of stations and frequency, this average was chosen as an indicator of long-term trends. However, discrete PSP events are better measured by individual values and probably would not last over a three-month period.

RESULTS

Five-year running averages since 1945 of the five environmental parameters are shown in Figure 2. By visual inspection, the parameters covary approximately between the warm/dry (positive PNI) and the cold/wet (negative PNI) regimes in the Pacific Northwest (Ebbesmeyer et al., 1989). Note that the Oyster Condition Index varies inversely with the other parameters.

Warm/Dry Climate Regime

When the SND values are positive (except the Oyster Condition Index, which is negative), winds advect subarctic water to higher latitude and longitude along the North American coast, while decreased winter storm activity causes lessened Pacific Northwest precipitation in concert with increased water temperatures. Meanwhile, the biological parameters show that sockeye salmon return preferentially around the northern end of Vancouver Island (through Johnstone Strait), the oyster condition in Willapa Bay decreases, and PSP shellfish toxicity in Sequim Bay rises above normal.

Cold/Wet Climate Regime

When the SND values are negative (except the Oyster Condition Index, which is positive), subarctic water drifts to lower latitude and longitude, precipitation increases, and water temperatures decrease. In this regime, sockeye salmon mostly return around the southern end of Vancouver Island (through Juan de Fuca Strait), oysters are plumper, and PSP shellfish toxicity decreases.

June through August 1964-1991 average toxin concentrations are shown in Figure 3. The five-year running average, accounting for 39 percent of the total variance of the annual three-month averages, increases rapidly during 1975-1980, from a lower plateau during 1964-1975 to a higher level during 1980-1991. During 1964-1975, toxin concentration averaged 155 μg toxin/100 g (standard deviation = 111 μg toxin/100 g) shellfish meat, whereas during 1980-1991 it averaged 414 (standard deviation = 186 μg toxin/100 g shellfish meat). Between the two decade-long intervals, PSP toxin concentration increased approximately threefold.

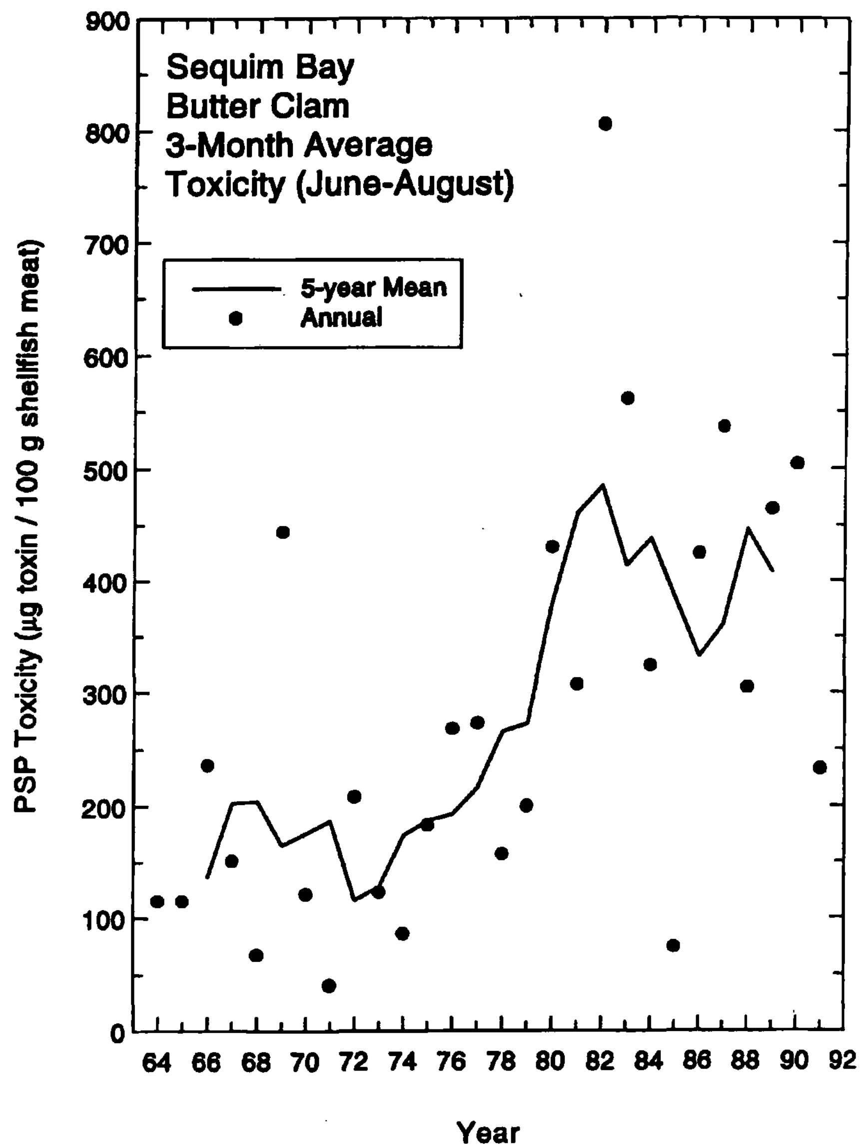

Figure 3. June-August PSP toxin concentration in butter clams. Three-month averages (June, July, August; dots) of maximum PSP toxin concentration in Sequim Bay butter clams during 1964-1991. Line represents the five-year running average.

DISCUSSION

By averaging standard normal deviates (SND) over five-year blocks of time, the covariation of many environmental parameters may be examined conveniently. Though this method leads to succinct descriptions of the cold/wet and warm/dry regimes, it does not provide the physical and biological causal linkages between the parameters. Nevertheless, the threefold change in toxin concentration between decades, together with other parameters used in this paper, reinforces the concept that the physical and biological environment oscillates between warm/dry and cold/wet regimes.

In a recent examination of the Oyster Condition Index, the Pacific Northwest index (PNI) was extended to include most of the 20th century (1900-1993; Ebbesmeyer and Strickland, 1995). This record shows approximately four 20-year long-term fluctuations in the present century. Though the decadal cycles vary in duration, the PNI suggests that these quasi-cycles may persist. Assuming this persistence is not an artifact of a short climate record and, further, that global warming does not alter the cycles' characteristics, it seems reasonable to predict that the Pacific Northwest warm/dry regime will revert soon to the cold/wet regime. If this happens, we anticipate added subarctic water off the Pacific Northwest coast, cooler water temperatures, more Fraser River sockeye salmon returning via Juan de Fuca Strait, oysters becoming plumper, and butter clams retaining less PSP toxicity.

We are still a long way from predicting outbreaks of PSP and providing early warnings of toxic conditions to shellfish growers and recreational shellfish harvesters. One of the key pieces of information still lacking is a detailed understanding of specific environmental cues that cause phytoplankton blooms. Although the general conditions (e.g., periods of relatively calm winds, reduced mixing, abundant nutrients and adequate light) under which blooms occur have been known for many years, the detailed processes that cause one algal species to bloom from among many, that sustain or terminate a bloom, and that cause the relative timing of blooms, remain a mystery as do the linkages to the Oyster Condition Index.

Therefore, we propose a field program to study the dynamics of bloom formation in *A. catenella* to determine what factors cause sustenance of the bloom and to identify the cues that cause the die-off or dispersal of the cells. In order to carry this out, a multidisciplinary team of phycologists, hologicalists, physical oceanographers, molecular geneticists, chemists, and ecologists must be in place before blooms start. However, the impracticality of this operation can be overcome only if a bloom of *A. catenella* can be reliably predicted at a specific location. For the first time, through records of PSP activity in shellfish collected for public health and regulatory purposes, such a location has been found (Chiang, 1985; Chiang, 1993). For the past eight years, outbreaks of PSP in shellfish (mussels) have been documented within a two-week period in mid-April in the waters surrounding Gilford Island on the northern end of Johnstone Strait in British Columbia. Thus, a well prepared team of interdisciplinary scientists could collect information that would further our understanding of algal blooms and lead us closer to predicting PSP outbreaks and other deleterious blooms.

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HARMFUL ALGAL BLOOMS AND FINFISH RESOURCES IN PUGET SOUND

Jack Rensel[1]

INTRODUCTION

Several harmful algal blooms (HAB) species have economic and biological importance to finfish resources by causing fish kills or biotoxin accumulation in the food web. These problems are apparently less prevalent for wild finfish in Puget Sound than in other U.S. coastal areas, but there is uncertainty regarding their significance here. Worldwide at least a dozen genera of microalgae have been involved in mortality of wild or aquaculture fish (Hallegraeff, 1991). Several of these genera occur in Puget Sound, although not all have been implicated in fish kills locally (Table 1).

Table 1. Fish-killing phytoplankton species known to be present in Puget Sound; those with an asterisk have caused documented fish losses in Puget Sound. The second column relates the concentration suspected to be harmful to fish and the etiology of harm.

Category and Species	Harmful Concentrations & Etiology	References
DIATOMS		
*Chaetoceros concavicornis** and *C. convolutus** and possibly others of the subgenus Phaeoceros such as *C. danicus*	> 2-5 cells/ml for salmonids, depends on chain length. Cells lodge between gill lamellae causing mucus production, irritation & leads to blood-hypoxia/anoxia	Bell, 1961; Rensel, 1992; 1993a Albright, 1993;
DINOFLAGELLATES		
Alexandrium catenella	unknown; acute mortality to farmed fish not well documented or prevalent; chronic, food web problem with wild fish	White, 1980; Mortenson, 1985 (for *A. tamarense*); Erickson, 1988
*Ceratium fusus**	unknown; gill irritation, poorly understood	Rensel and Prentice, 1980
Noctiluca miliaris (= *N. scintillans*)	variable; unionized ammonia causes gill damage and other problems for fish	Okaichi and Nishio, 1976
PRYMNESIOPHYTE FLAGELLATES		
Chrysochromulina polylepis	unknown; causes gill damage and osmoregulatory problems	Estep and MacIntyre, 1989
Phaeocystis pouchetii	unknown; irritant substances and the alga's mucus can clog gills	Gaines and Taylor, 1986 Smayda, 1989

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Table 1 continued.

RAPHIDOPHYTE FLAGELLATES		
*Heterosigma carterae** (Formerly *H. akashiwo*)	probably variable, in most cases >750 to 1,000 cells/ml; cause of fish death unknown, may be similar to *Chattonella*	Black et al., 1991; Taylor and Haigh, 1993; Tanaka et al., 1994
SILICOFLAGELLATES		
Dictyocha speculum	unknown; siliceous skeleton may irritate gills, possible toxin action too	Larsen and Moestrup, 1989
UNKNOWN ALGAL SPECIES		
Net pen Liver disease*	unknown; chronic losses possibly caused by a microcystin-producing alga	Kent, 1990
unidentified dinoflagellate*	mortality of delayed-release net-pen salmon in Hood Canal in summer, 1993	R. Horner and J. Rensel, unpublished data

The table shows that little is known regarding exposure concentrations of most microalgae that kill fish; the causes of physiological harm are also poorly documented in several cases. Table 1 should not be considered all-inclusive, as there may be other microalgae in Puget Sound that can cause fish kills. Unexplained losses of hatchery-raised and wild fish have been reported from Puget Sound in recent years. For example, an unidentified dinoflagellate was responsible for losses of salmon smolts in a state-operated net pen in Hood Canal during 1993 (R. Horner and J. Rensel, unpublished data). Two types of harmful microalgae problematic in Puget Sound, *Chaetoceros* spp. and *Heterosigma carterae*, are discussed below.

Chaetoceros spp.

The marine diatom genus *Chaetoceros* is separated into two subgenera by the presence (*Phaeoceros*) or absence (*Hyalochaete*) of long, partly hollow setae or primary spines that contain chloroplasts. *Phaeoceros* species, such as *C. concavicornis* and *C. convolutus*, have more robust setae and frustules than *Hyalochaete* species, and the setae are armed with short secondary spines that point toward the distal ends of the primary setae (Cupp, 1943). With few exceptions, the chain-forming *Phaeoceros* species are responsible for mortality of fish, although dense blooms of *Hyalochaete* species were implicated in the poor survival of one group of salmon smolts in Port Angeles Harbor net pens in 1988 (R. Elston and J. Rensel, unpublished data).

The first reported case of *Chaetoceros*-caused fish mortality involved wild lingcod (*Ophiodon elongatus*) that were captured and held temporarily in fishermen's cages in British Columbia (Bell, 1961). Subsequently these diatoms have been involved in occasional losses of net-pen salmon, including a major loss near Cypress Island in 1987 (Rensel et al., 1989; Horner et al., 1990). It has been suggested that harmful *Chaetoceros* setae break off the cells and enter the gill tissue butt-end first; the apically pointed secondary spines on the primary setae may then act like barbs on fish hooks (Bell, 1961). This hypothesis and reference is often repeated in the literature but is based on only a few samples of wet-mounted gill tissue. Rensel (1992, 1993a) used scanning electron microscope techniques to show that penetration of the gill tissue by *C. concavicornis* was uncommon. Rather, chains of cells tended to lodge between the secondary lamellae and be present in the surrounding gill mucus. Blood-gas studies showed that affected salmon had severe blood hypoxia as a result of mucus production during acute exposure or physiological damage to the gills after longer-term exposure. Longer chains of *C. concavicornis* caused significantly

lower blood-oxygen partial pressures compared to fish exposed to shorter chains. Longer setae associated with longer chains were apparently more likely to become wedged in the gills and stimulate mucus cell release, lesions and epithelial damage.

Salmon respond to *C. concavicornis* exposure with an immediate and periodic cough response that diminishes slightly in frequency over time (Rensel, 1992, 1993a). This is similar to the fish coughing caused by many environmental irritants and chemicals (Heath, 1987). Coughing and mucus production act in concert to help clear the gills of the diatoms. Long strings of mucus were seen trailing from the gills of live fish during the 1987 Cypress Island fish kill.

Short-term laboratory exposure to as few as 10 cells per ml of *C. concavicornis* caused a rapid increase in mucus cell discharge on the gills as well as a severe hypoxia and elevated carbon dioxide content in the blood of Atlantic salmon (Rensel, 1992; 1993a). Long-term exposure to < 5 cells/ml of harmful *Chaetoceros* in net pens has been reported to increase disease and mortality of farmed salmon (Albright et al., 1993), although sampling in this study may not have been frequent or extensive enough to assure that higher concentrations of the diatoms did not occur. Nevertheless, it is clear that low concentrations of these diatoms can kill salmon; hence the term "bloom" is not always appropriate when referring to harmful *Chaetoceros*-caused fish kills.

It is likely that harmful *Chaetoceros* have caused mortalities of wild and hatchery-released fish. South Hood Canal and Dabob Bay/North Hood Canal are areas where these harmful diatoms often occur (Rensel et al., 1989; Rensel Associates and PTI Environmental Services, 1991; J. Postel, unpublished data). During the fall of 1990 a mixed water column in north Hood Canal containing *Chaetoceros concavicornis* to at least 40 m correlated with the otherwise unexplained mortality of migrating adult chinook salmon (Rensel Associates and PTI Environmental Services, 1991). In southern Hood Canal, mortality of juvenile salmon in sea water pumped from a subsurface depth was due to harmful *Chaetoceros*; this suggests the possibility of a recurring problem for wild smolts moving through the area. Harmful *Chaetoceros* often occur in late spring and again in September or October, although they may be present at any time of year in Pacific Northwest waters (R. Horner, unpublished data; Rensel, 1992). Their geographic range and relationship to occasional fish kills in Puget Sound are not well defined.

Heterosigma carterae

This raphidophyte flagellate is known worldwide as a fish killer and has caused significant mortality of net-pen salmon in Puget Sound in 1989 and 1990 after several years of problems in British Columbia waters. *H. carterae* may have been present for at least several decades in Puget Sound before the 1989 and 1990 blooms. Taylor and Haigh (1993) note the species has appeared with great regularity in late spring in the Strait of Georgia since 1967, when surveys were first initiated. Appearance there coincides with a rise in water temperature above 15°C and a decline in surface salinity to less than 15 psu. The 1989 bloom in Puget Sound was apparently restricted to the northern areas of Puget Sound and the San Juan Islands, but the July 1990 bloom involved large areas of northern, central and southern Puget Sound. In 1993, a bloom of *H. carterae* was recorded in Budd Inlet, the southernmost extreme of Puget Sound.

Recent laboratory studies suggest that reduced salinity plays an important role in bloom formation of *H. carterae*. By simply adding a small amount of distilled water to the surface of vertical columns containing the alga, large quantities of the cells accumulated near the surface (Hershberger et al., in prep.). The importance of freshwater-induced vertical stratification in field studies of *H. carterae* has been observed by Taylor and Haigh (1993).

Heterosigma blooms apparently require quiescent weather conditions, as was experienced immediately prior to and during the 1989 and 1990 blooms in Puget Sound. Strong vertical stratification of the water column due to fresh water and perhaps solar heating also seem to be a prerequisite. The September 1989 bloom was apparently associated with the Fraser River plume in Northern Puget Sound. The July 1990 bloom occurred in an extremely calm, warm period in early July following a June when Puget Sound lowland precipitation was 51 percent more than normal (NOAA, 1990). Moreover, routine monitoring in Admiralty Inlet approximately 10 days before the 1990 bloom confirmed that the surface layer was warm

(near 15°C) and of reduced salinity (19.5 ppt) (Janzen, 1992). This is significant given the mid-Puget Sound location of this sampling station, remote from creeks and riverine sources of fresh water. Other regional stations had similar values. Macronutrient content in the surface layer was undetectable, but *H. carterae* is capable of vertical migration, moving up to 1 m/hr to obtain nutrients from subsurface depths.

In mid-July of 1993, a bloom of *H. carterae* occurred in the Port Orchard/Brownsville area east of Bainbridge Island. Antecedent rainfall and quiescent weather conditions were similar to those of the 1990 bloom. The bloom appeared to increase in size for several days, but an abrupt weather change, including strong south winds, correlated with the rapid termination of the bloom. Soft bottom sediments of this protected area may be a seed bed for some of the blooms.

The physiological cause of fish mortality from *H. carterae* exposure is unknown despite several laboratory studies that used clones or cultures taken from local fish kills. Histopathology of gills of moribund subadult salmon from net-pen kills usually show mucus buildup and major damage to the epithelium, but not in one case with juvenile fish where a labile icthyotoxin was suspected as the cause of mortality (Black et al., 1991). However, no toxin has been detected in the edible tissues of any affected fish. Although *H. carterae* grows well in culture, most laboratory bioassays here and abroad have yielded few fish deaths even when fish are exposed to very high concentrations of cells or conditioned medium. Several authors have suggested that the fish-killing mechanism may be similar to that of the related alga *Chattonella antiqua*, which occurs in Japan. Superoxide anion radical and hydrogen peroxide produced by the alga reportedly strips the fish gill of mucus and leads to fatal osmoregulatory stress (Tanaka et al., 1994). Yet this does not fit with current knowledge of salmonid physiology because the normal, unstressed condition is to have little or no mucus on the gills (Handy and Eddy, 1991). A possible advance regarding laboratory-induced toxin production by *Heterosigma* was reported in 1994, although few details are available at this time (R.A. Cattolico, pers. comm., 1994).

H. carterae blooms may extirpate or outcompete virtually all other algal species in the upper water column (Taylor and Haigh, 1993). Its effect on larval or other fish frequenting shallow depths has not been studied, but there is evidence that wild fish or hatchery-released fish have been harmed. There were several reports of wild fish kills and wild fish acting in a distressed manner in Port Townsend Bay and the Strait of Juan de Fuca during the 1990 bloom. Limited aerial surveys failed to validate the reports (R. Allen, J. Rensel, survey of 12 July 1990), but the surveys were restricted to the Port Townsend area, and there was a lag of at least one day between the reports and the surveys. Dead adult chinook salmon were seen by local boaters in Bellingham Channel during the 1989 bloom, but no tissue samples were collected.

More recently, in the fall of 1994, chinook, coho and summer chum salmon as well as several marine fish species were killed by a *Heterosigma* bloom in upper Case Inlet of southern Puget Sound. It is a shallow area where several streams enter Puget Sound and the fish were apparently unable to escape the bloom. The full extent of fish loss was unknown but numbered at least in the hundreds. State agency and university researchers were not notified of the kill until well after it began, reducing their ability to collect useful data.

DETECTION AND MITIGATION OF FISH KILLS AND ALGAL BLOOMS

Detection of wild fish losses due to HABs in Puget Sound is a difficult task. Affected wild salmon most likely sink to the bottom, similar to HAB-killed salmon in net pens. Usually shoreline residents or boaters do not notice fish losses or will notify state agencies too late for adequate data collection during a bloom. In some cases, residents have mistakenly supposed that dead adult salmon are simply spawned-out fish, particularly in areas with creeks and rivers having salmon runs. Fish mortalities can occur in areas with less shoreline development, such as North Hood Canal, so that fewer people notice dead fish. Migrating adult salmon do not necessarily travel in large schools (e.g., chinook salmon), so an occasional dead fish does not seem significant. A partial solution to these detection problems is public and government agency education and resource agency planning before the occurrence of HABs.

Reducing non-point and direct discharges of nitrogen into nutrient-limited marine waters may be viewed as one means of prevention or mitigation of some types of HABs. A review of several HAB case

histories worldwide suggests that some, but certainly not all, HABs are associated with increased coastal eutrophication (Rensel Associates and PTI Environmental Services, 1991). The connection may be more related to rates of tidal flushing and vertical stratification in specific areas than to characteristics of a given HAB species. For example, nutrient discharge is an important factor controlling the extent of *Heterosigma* blooms in the Seto Inland Sea of Japan (Honjo, 1993), but there is no evidence of this in the main basins of Puget Sound. Yet poorly flushed and nutrient-sensitive areas of Puget Sound have minimal nitrogen supply rates in clement weather, which may limit algal production (Yake, 1981). Therefore HABs can be stimulated by increased nitrogen loading. Rapid urbanization, poor agricultural or logging practices and municipal discharges have in some cases resulted in very large increases of nitrate loading to Pacific Northwest streams and rivers (e.g., Smith et al., 1987; Harr and Fredriksen, 1988), but few nutrient discharge data have been analyzed with regard to eutrophication or HAB trends in nutrient-sensitive areas of Puget Sound.

Monitoring and experimental data suggest that very low or undetectable concentrations of nitrogen in surface and subsurface waters of nutrient-sensitive areas of Puget Sound have limited the geographic range or activity of paralytic shellfish poisoning (PSP) caused by the dinoflagellate *Alexandrium catenella* (Rensel, 1993b). Salmonid smolts and other phytophagous finfish may be at risk from saxitoxins accumulated by zooplankton that have consumed *A. catenella.* This has been demonstrated in the laboratory (Erickson, 1988), but not as of yet in Puget Sound. It follows that phytophagous fish in these areas are at risk if PSP activity increases due to increased nitrogen loading. With regard to the occurrence of harmful *Chaetoceros*, however, there are no data suggesting an association with nutrient discharge or with a specific type of area, nutrient-sensitive or otherwise. For example, these diatoms occur in both seasonally nitrogen-limited South Hood Canal and nitrogen-replete North Hood Canal.

Harmful *Chaetoceros* are difficult for fish farmers to detect because a lethal concentration of cells may have no effect on easily measured parameters such as water transparency, dissolved oxygen, pH, etc. The vertical and horizontal distribution of cells is difficult to ascertain without extensive and time-consuming microscopic cell counts. Automated cell counting techniques are not possible due to the large size and spines of these diatoms. A simple means to detect the presence of harmful *Chaetoceros* at fish farms is microscopic examination of wet mounts from gill scrapings. Other techniques such as histopathology are slow, expensive, and not appropriate for routine detection on the gills because the diatom cells occur in the interlamellar spaces and on the epidermis and may be washed away during the extensive tissue preparations that are required.

Blooms of harmful microflagellates or dinoflagellates that occur in high concentrations are often easier for fish culturists to identify and manage because visual surveys from boats or airplanes can be used to define their geographic limits. This facilitates towing of net pens to unaffected areas such as in 1990 when pens were towed from Rich Passage into Colvos Passage. These blooms are often restricted to near-surface depths allowing for the pumping of algal-free deep water into the pens equipped with surrounding skirts; onshore or upland facilities may have water intakes at several depths to avoid HABs. Because *Heterosigma* blooms occur in surface waters during clear weather, sea-surface temperature and chlorophyll-*a* sensing satellites that are scheduled to be launched may be useful to track and predict the distribution of these blooms.

RESEARCH NEEDS

There is a need to investigate wild fish kills involving HABs more completely and expeditiously and to document accompanying hydrographic and meteorological conditions. These investigations can form a basis for understanding HAB dynamics, trends and possible connections with land and riverine management practices. Nitrogen loading trends for streams, rivers and municipal discharges should be examined for nutrient-sensitive areas of Puget Sound.

The physiological causes of fish mortality due to *Heterosigma* remain to be discovered. Larvae or juveniles of marine fish and salmonids that use shallow embayments during late spring through fall may be at risk to the apparent recent spread of *Heterosigma.* Juvenile and adult salmon and marine fish in Hood

Canal and perhaps elsewhere in Puget Sound appear to be at risk to harmful *Chaetoceros* occurrence, but this remains to be quantified. Finally, field studies are recommended to test the importance of saxitoxin accumulation from the dinoflagellate *Alexandrium catenella* to zooplankton and throughout the food web to salmon and other predators.

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PUGET SOUND RESEARCH '95

SESSION 4A
SHELLFISH

Session Chair:

Duane Fagergren, Deputy Director
Puget Sound Water Quality Authority

PANEL: SHELLFISH

CHAIR

Duane Fagergren, Deputy Director, Puget Sound Water Quality Authority

PANELISTS

Jack Lilja, Technical Expert, Shellfish Program, Washington Department of Health
Greg Ma, Supervisor of Microbiology and Aquatic Toxicity Testing, Seattle Metro
Bill Dewey, Director of Public Relations, Taylor United, Inc.
Mason Morisset, Legal Counsel for Indian Tribes of Washington State
Judith Freeman, Deputy Director, Washington Department of Fish and Wildlife

Duane Fagergren, Deputy Director, Puget Sound Water Quality Authority:

The first speaker is Jack Lilja with the Washington Department of Health Shellfish Program. His topic is the fecal pollution indicator sytem.

Jack Lilja, Technical Expert, Shellfish Program, Washington Department of Health:

Today I will focus on the public health significance of the fecal pollution indicator currently in use, the fecal coliform group.

I will talk a little about the history of shellfish-borne disease, speak about the effectiveness of the current indicator in predicting health risks due to shellfish consumption, and suggest some approaches toward developing a better system of classifying shellfish growing waters.

The National Shellfish Program (NSSP), which provides the framework for state regulatory programs, was initiated in 1925 to deal with outbreaks of typhoid fever associated with shellfish consumption. Improper disposal of human waste was the main cause of these outbreaks.

Typhoid fever and other pollution-associated bacterial illnesses continued to be the predominant cause of shellfish-borne disease through the 1950s.

In the 1960s, we began to see a change in the type of agents responsible for the outbreaks. Human enteric viruses, primarily hepatitis A, and later Norwalk virus, became the major cause of shellfish-borne disease. There were also numerous outbreaks occurring about the same time in which the causative agent was unknown. Based on symptoms and incubation period, they were presumed to be caused by other human enteric viruses.

In the 1970s and 1980s, naturally occurring marine pathogens, primarily bacteria of the genus Vibrio, emerged as one of the leading causes of illness related to shellfish. This group joins the human enteric viruses as the leading causes of shellfish-borne illness today.

The last major group of disease-producing agents are the marine biotoxins. This group causes the illnesses known as paralytic shellfish poisoning, amnesic shellfish poisoning, neurotoxic shellfish poisoning, and diarrhetic shellfish poisoning. These biotoxins are responsible for an increasing number of illnesses worldwide.

Pollution associated with bacterial pathogens, such as Salmonella, Shigella and Vibrio cholerae are relatively insignificant today. Interestingly, they are the group of organisms most readily predicted in the marine environment by our current indicator system, the fecal coliform.

Through all the changes in the causative agents of shellfish-borne disease, there have been very few changes in the indicator system we are using. The major changes have been:

1. We have gone from using coliforms as supportive data in classifying growing areas to using them as absolute standards.

2. We have switched to using the fecal coliform group rather than total coliforms.

When pollution-associated bacterial pathogens from large point source discharges were the main cause of shellfish-borne illness, the coliform indicator system worked pretty well. However, as human enteric viruses and naturally occurring marine pathogens began to emerge, the usefulness of the coliform indicator diminished—that is, its use diminished as an indicator of problems related to shellfish consumption and not necessarily as an overall indicator of water quality. Let's examine some of the problems with the current system.

1. The indicator system was originally designed for large point source discharges of inadequately treated sewage. Therefore, it is poorly suited to accurately assessing the range of the more variable and indiscrete sources we now have to deal with—mainly the non-point sources.

2. The indicator system was originally designed to provide supportive data to a comprehensive sanitary survey. It was not designed to be the major determining factor in classifying water, which is how it is used today. Bacteriological data must be viewed in context with other information from the sanitary survey to establish accurate classifications.

3. The coliform indicator is of no value in predicting the presence of naturally occurring marine pathogens and of very little, if any, value in dealing with human enteric viruses—the two leading causes of shellfish-borne disease. As an example, the two most recent outbreaks in Washington were traced to areas where fecal coliform monitoring had occurred with no indication of problems. Both outbreaks were ultimately attributed to viruses.

4. The fecal coliform indicator does not distinguish between human and non-human sources. Research continues to suggest that the risk of viral infection from animal waste is less than that associated with human sewage. Certainly there are bacterial pathogens from animals that can cause illness in humans, but viruses are much more host-specific.

5. Fecal coliforms are able to multiply in the environment, including marine water and shellfish tissue, which can result in misleading data.

6. Fecal coliforms are not exclusively intestinal in origin. Klebsiella, for instance, which is associated with pulp mill waste, gives a positive fecal coliform reading under normal lab procedures.

What can we do about dealing with some of these problems with the current indicator system? The approach that was taken by the National Indicator Study—which is currently on hold because of lack of funding—is a good one.

I will briefly go over the goals of that study.

The overall objective was to improve the current water quality-based management system by providing a more reliable assessment of public health risk associated with the consumption of raw shellfish.

This was to be accomplished in a number of ways:

1. By developing microbial and chemical tools to refine and improve our ability to assess the relative public health importance associated with the discharge of fecal material from different sources into molluscan shellfish harvest areas.

2. By selecting the best group of indicators of human health risk associated with the consumption of raw molluscan shellfish. We need to get away from the concept of one indicator.

3. By determining the efficacy of the current indicator system for the management of molluscan shellfish waters to protect public health.

4. By identifying indicators specific to human and animal fecal contamination.

5. By confirming or refuting the widely held perception that significant differences exist in potential public health risk associated with human, domestic animal, and wild animal waste.

6. By determining whether shellfish exposed to animal fecal contamination, particularly runoff from areas frequented by wild animals, poses a significant health risk.

7. By improving our ability to identify illness-causing organisms in outbreaks by developing laboratory methods to isolate viral pathogens, such as Norwalk virus and hepatitis A.

8. By establishing, if possible, a dose-response relationship between an indicator or group of indicators and the occurrence of a specific molluscan shellfish-borne illness.

9. By determining differences in indicator organism or pathogen accumulation among molluscan shellfish normally consumed raw.

If we continue to pursue these objectives, I believe we can develop a system of shellfish growing-area classification that is based on health risk and that reflects more accurately the public health significance of fecal pollution.

Fagergren: The next speaker is Greg Ma, who is supervisor of Microbiology and Aquatic Toxicity Testing at Metro here in Seattle. Greg is going to give us an update on two case studies of fecal coliform source-typing.

Greg Ma, Supervisor of Microbiology and Aquatic Toxicity Testing, Seattle Metro:

I'm in complete agreement with all the points Jack just made. And actually, I might be able to expand on one of the last points he talked about, and that's modifying or improving methodologies for taking a look at source tracing, or where these coliforms may be coming from. We undertook a couple of different types of studies in looking at research methodologies in conjunction with the Department of Environmental Health at the University of Washington. So what I'm going to be talking about is not work that was done exclusively at Metro. It's technology that was developed at the University of Washington, and it also relies on some work that's been done over at Department of Health laboratories at north Seattle.

One of the problems we've been faced with for quite a long time is determining whether fecal contamination is emanating from Metro's treatment plants or any of the conveyance systems that we may have in place—or whether it's coming from somewhere else. We've got concerns about impacts on shellfish areas and receiving waters, both fresh and marine.

The coliform indicator, as Jack has pointed out, doesn't do that very well for us. It gives us an idea about contamination, and truly elevated levels will give us a pretty good indication that maybe an was contaminated by some sort of fecal source. But it doesn't really give us very strong proof. The fecal coliform group is a broad array of different types of organisms that have one chemical characteristic in common. Not all of them come from fecal sources. In the past we've looked at a couple of different methodologies for sorting that out. We also have a couple of new methods we're looking at, particularly in the area of sludge and compost testing, to see if regrowth is occurring. That's a common problem as well, and runoff may lead to a problem in receiving waters.

That gives us some more information, but again, it doesn't really tell us where things are coming from. One of the more promising things has been fatty acid analysis by gas chromatography. This technique has allowed us to take a look at the cell wall components of particular organisms. In one study, Department of Health and UW had taken a look at the *E. coli* organisms associated with the 0157H7 outbreak—the hamburger outbreak everybody's familiar with in the state of Washington. This new technology allows us to take a look at the organisms and determine whether they're all from the same source.

The results they came up with demonstrated very good clustering of the outbreak strains. In fact, the Department of Health was able to demonstrate that a number of the patients who contracted this illness carried the same clono-strain, based on fatty acid analysis. There were other strains associated with the meat products that were similar—that carried the same named species—but they were not related to the outbreak. They were also strains that could cause the illness. So this tool allowed us to differentiate much more precisely among the types of strains and actually to trace the epidemiological source.

Another approach, in addition to this fatty acid analysis, was to take a look at the ribosomal tracking, the DNA components of these strains. When they did that, the University of Washington researchers found that they could group and trace these strains very accurately. Using that gene-tracking technology, we undertook to examine one of the urban watersheds in Seattle where we'd had chronic elevated fecal coliform counts. The study was done in Carkeek Park, where we have a sewage treatment plant that has recently been converted to stormwater treatment. But we've historically had a problem with very elevated fecal coliform counts in that watershed, flowing down through the steam, across the beach, and out to the Sound.

The question has always been, where does that elevated count come from? Baseline levels are somewhere on the order of about 10 to 20 fecal coliform organisms per 100 milliliters of water. But during storms, that jumps up to about 8000, 9000—in some variances, 10,000—organisms per 100 milliliters. That's a little bit higher than we're content with. There's been chronic concern that, because we have a plant there, we might be contributing as a source. But we found that the counts occur above the plant, upstream, as well as downstream of the plant.

Concern then centered on the possibility of leaking septic tanks or broken sewer lines—or any other flushing that might be occurring. We also suspected that animal sources or vegetation sources might be the cause. So we designed a small pilot study to look at a number of different potential sources of fecal contamination: animals, dogs, cats. There was a duck pond that drained into the system; we took a look at the water samples from there, and also duck fecal material. We looked at vegetation sources for fecal coliforms.

And we isolated, specifically, *Escherichia coli* (*E. coli*), which makes up a significant portion of the fecal coliform population. We took those *E. coli* isolates—about 300 of them—and we broke them apart, took a look at their DNA patterns, and found about 176 different types of patterns. What we discovered was that within a host source, the patterns were fairly specific and unique. For example, in all of the duck fecal materials, we found that there were 13 different ribotype patterns. Out of dog sources, we found there were 16 different ribotypes in the limited number of samples we looked at. Cats gave us 13 different patterns. From sewage samples we found 29 different patterns. And from vegetation sources we found 12 different patterns.

Then we took a look at the water coming through the stream and tried to match the ribotype patterns from those isolates to the source ribotype patterns. We found that we had matches in a number of the different animal sources, and only one with the sewage sources. That one, from the sewage source, also matched very closely with an isolate that came from the dog pool.

What this information gave us was a very tight correlation with animal sources as the potential cause of elevated fecal contamination. The most prominent correlation came with cat fecal material. We had the city of Seattle do some estimation based on the number of licensed dogs, cats, and other pets, along with a rough estimate of how much fecal material these animals would produce. It was a staggering figure. I can't believe that much is actually contained in one park. But we've got some fairly good evidence, considering ours was a very small study with a limited number of samples. We're hoping that we can expand this tool and use it in the future to take a look at other sources, particularly non-point sources that might be affecting marine waters and shellfish growing areas.

I'd be happy to take any questions now.

Q: Do you have a report on this study?

Ma: Yes, we do. The study was commissioned by the city of Seattle and was let out on bid to Herrera and Associates. I've got a copy of that. If you'll leave me your card, I'll send you one.

Q: I live in Carkeek Park, and every day at high tide, there's a huge stock of what looks like raw sewage. If it doesn't come from Metro I'd be greatly surprised. The suggestion that the ducks are behind this, or perhaps the dogs in the park, seems contrary to what I've observed.

Ma: I'll accept that. In fact, at our laboratory, I have on occasion looked out the window and seen this plume coming down the ship canal towards us, and have wondered where that comes from. Apparently, we have a CSO—a combined sewer outflow—down the hill from Queen Anne just a little bit upstream from us, and we experience the same phenomenon. Surprisingly enough, this particular CSO is right next to the Metro Industrial Waste Office. So we're still working on the problems. We recognize they're there. The evidence we have so far is leading us to believe that it's a source other than Metro. We are still investigating that, and we're trying to take more samples associated with our treatment plant to make sure that we are not the culprits.

Fagergren: Bill Dewey of Taylor United will speak next on hatchery techniques.

Bill Dewey, Director of Public Relations, Taylor United, Inc.:

Over the past 20 years, the shellfish industry in Washington state and throughout the West Coast of the United States has come to rely very heavily on shellfish hatcheries for its seed. In fact, the technology that's evolved in these hatcheries has made Washington state the leading state in the nation for Pacific oyster and Manila clam production.

This morning I'd like to talk briefly about the bivalve life cycle. You'll need to understand that to understand the rest of my talk. Then I'll turn to the history of seed production in the state and the state of seed production today. And finally, I'll talk about what I consider the research and development needs of hatcheries.

The bivalve life cycle. Typically, shellfish begin gametogenesis—or developing the sperm and the eggs—in the early spring. They continue this through early summer, to where they release the gamete to the water in mid- to late summer, where fertilization happens externally. What follows is typically a two- to three-week larval period, during which they're free-floating plankton in the water. This is followed by settlement and metamorphosis, which, in the case of Pacific oysters, involves cementing and attachment. With Manila clams, or mussels, it involves attaching with the byssal thread.

For those of you who are interested in sex, I'd like to offer a few points of trivia. For one, a female Pacific oyster is capable of producing upwards of 80 million eggs. With fertilization taking place externally, a lot of eggs are required to assure fertilization and to assure there will be survival of at least a few of them through their larval period.

Second, you might be interested to note that a Pacific oyster can be either a female or a male and can change at will. I imagine there are a few of you who have at least fantasized about having that ability. Too bad for the oyster's sake that fertilization happens externally in the water—in the cold water, I might add. Then again, they do get to look forward to one hell of an orgy every summer because in order to ensure fertilization, everybody has to spawn at one time. If you happen to be fortunate enough, or perverted enough, to be there when they do it, you can see the whole bay turn creamy white with the gametes as they're released.

Following the spawning, there are several stages of larval development. Once they've built up enough shell that they're no longer buoyant, they settle. Then metamorphosis takes, where the seed is attached. You can see it on these slides. These actually are several months old, after the oysters have attached to the mother shell. You can see the spat attached to these shells.

When the state shellfish industry began in the mid-1800s, its focus was mainly on the harvesting of wild Olympia oysters (*Ostria lurda*). It wasn't until after 1890 that efforts were directed by the industry to improving the seed settlement. The industry discovered that by diking the tidelands to hold the water in when the tide went out, they could improve settlement and survival of these young Olympia oysters. Dikes in the higher intertidal area would be used for catching seed; then typically, after a couple of years, the seed would be gathered and moved to lower dikes for fattening prior to marketing.

The Olympia oysters are very sensitive to environmental conditions and to pollution. Without the water held in by the dikes, they were susceptible to cooking in the summertime and freezing in the winter. With the influx of pulp mills into Puget Sound, it soon became a losing proposition to try to cultivate them at all. So a hardier oyster species was sought, and after failed attempts with the Atlantic oyster, the Japanese or Pacific oyster was introduced in 1921. It was found to grow and survive very well in Puget Sound; however, it didn't very effectively complete its reproductive cycle because of the cooler water temperatures here. Consequently, for the following 50 years, seed was procured from Japan each year and barged to Washington for distribution among the growers.

The Manila clam, which is also a popular commercial species in the state, was introduced accidentally. It came along as a hitchhiker in these cases of Japanese oyster seed. It's established itself well throughout Washington state, and in fact has adapted better than the Pacific oyster where spawning temperature is concerned. The Manila clam reproduces in many areas. It's become the most intensely cultivated clam species in Washington—and the steamer clam of choice in the marketplace.

In the late 1960s there was a decline in the availability of Japanese oyster seed. The industry shifted its focus to collecting seed from a few areas in the Northwest that warmed sufficiently in the summer to allow for successful natural reproduction of the oysters. This was typically in Dabob Bay on the Hood Canal, Willapa Harbor in southwest Washington, and Pendril Sound up in British Columbia. Oyster growers would take strings of cultch—which is oyster shell with a hole punched in it, strung onto a galvanized wire—to these areas at a critical time when the larvae were in the water and ready to settle out.

By the mid-1970s, it was apparent to the industry that the natural spawning in these few areas was not dependable enough to sustain a growing industry. For this reason, hatchery technology evolved. Today, roughly 90 percent of the state's oyster production and 40 percent of the state's Manila clam production is initiated through hatcheries (that's an estimate on my part). The balance of the commercial production comes from "cultivation" of natural reproduction. I had the quotation marks inserted because I assumed I'd be coming after the tribal lawsuit talks; that definition of cultivation is the growers' definition, not Judge Rafeedi's definition.

In the hatchery we bring in the adult shellfish and manipulate their environment to make them think it's summertime and convince them to spawn. We elevate the temperatures and give them lots of algae to eat. This process is called conditioning. By having different adults at different stages of conditioning all the time, we can have animals ready to spawn weekly, year-round. We just have to light some candles, put on some romantic music, and turn down the lights, and you can imagine what happens when, in the controlled environment of a hatchery, you have a female oyster producing 80 million eggs. It doesn't take many oysters to supply the whole industry with seed—nor many hatcheries.

One of the downfalls in the hatcheries is the lack of a proven artificial diet, so we spend a good deal of our energy cultivating algae. These are the larvae tanks here, where the oyster larvae are grown in static culture. We grow a half-dozen different species of algae so that we can provide a balanced diet for the various larval stages in the hatchery.

In algae production, we use two different techniques. We use batch culture, where we start them in flasks, bring the flasks up to density, transfer to carboys, bring those up to density, then transfer to larger tanks, and then finally feed it out. We also use continuous culture bags. This is a technology we brought in from Great Britain. Here there's a continuous flow of pasteurized, nutrified sea water flowing in and constantly pulling algae out to feed the larvae. These bags typically will run for two or three months before we trash them out and start them again.

It's been fairly easy to learn how to culture the larvae of the various species for shellfish production. Where we suffer our greatest mortalities and focus much of our efforts is in getting animals through metamorphosis and the nursery stage, where we are typically holding them in intensive systems at high densities, trying to get them to a size sufficient for planting. Each species has its unique quirks.

With the evolution of hatchery technology, the industry's been able to make some pretty significant advances. This is one of our setting systems; that particular container has about 8 million Manila clams, causing the brown haze in the water in that settling tube.

The hatcheries have provided some significant advancements for the industry. For one, it gives us a consistent seed source for our oysters, clams, mussels, and a variety of other species. They've allowed us to work with genetic selection, so we can get improved growth rates and fatter, faster-growing oysters. We've also been able to produce sterile, or triploid oysters, which don't go through this *Scamana genesis*, and give us a more marketable oyster for raw consumption in summer.

The research and development needs related to hatcheries are as follows. First we must continue to develop and refine hatchery nursery techniques for our commercial species—that's an ongoing process for us. Next, we need improved broodstock management industrywide. Now that we have the hatchery technology, there's a real risk of inbreeding, a reduced gene pool, and the detrimental effects associated with that. The industry needs to come together better on its management practices there.

We're looking forward to commercial production of tetraploids for safer, more efficient triploid production. This is a new process that's evolving, which is more effective and safer than the existing treatment with this chemical cytochalasin B.

In addition we need improved hatchery nursery techniques for cultureless oyster production. This is particularly a problem for our company. Through the metamorphosis and nursery phase with raising tiny, single oysters, we have a very high mortality. We're doing some experimental work with flow-through larvae culture. Typically, we've always used static batch culture of larvae. But flow-through is resulting in some high-density cultures that are looking promising.

Finally, algae production is an ongoing research area for us, as well. We need to look at ways to grow higher cell densities. We need to look at continuous versus batch cultures. We need to consider alternative species that would grow better in our cooler climate (most of the species we raise now are warm-water ones). We need to look at the nutritious value of the algae pastes as well at more convenient ways to use it. People are growing algae and converting it into a paste that you can put in the refrigerator and feed when you need it. And finally we need to consider alternative feeds other than the algae; at this point, there are no successful artificial diets for the larvae when we're raising them in the hatchery.

In conclusion, I'd just like to say that the Washington shellfish industry has come a long ways in the past 100 years. We've been aggressive in technological advances, as well as in our battles to preserve water quality. If we can maintain water quality throughout the state, the hatcheries are certainly capable of providing us with more seed than we know what to do with. While it's not directly related to my presentation, I did assume I was going to be following Judith and Mason, and just wanted to offer that the Puget Sound growers are looking forward to a cooperative resolution to the Indian shellfish rights issue and once again being able to focus our efforts on research and development. Thank you.

Fagergren: That's a good lead-in. Mason Morisset is legal counsel for the Indian Tribes of Washington State. Judith Freeman is deputy director of the Washington Department of Fish and Wildlife. I think we'll start with Mason Morisset, and then have Judith Freeman run anchor.

Mason Morisset, Legal Counsel for Indian Tribes of Washington State:

I think it's important for scientists and technicians, as most of you are, to understand how much the science of Puget Sound has been and is being driven by law. I grew up in the Northwest, but I first moved to Puget Sound in the early 1960s, almost 35 years ago. We didn't have any Puget Sound Water Quality Authority. We didn't have any Clean Water Act. We didn't have many environmental laws of any kind.

People like Professor Bill Rogers, who got up earlier to complain about the sewage at Carkeek, wouldn't have had a job at the law school teaching environmental law because we didn't know what that was. When I went to law school at Berkeley, we never heard about the environment, except maybe in the context of a common-law right not have someone dump sewage on your property.

Those of you who have grown up with the Clean Water Act and the Puget Sound Water Quality Authority, and so on, need to realize that it hasn't been that long since there was no real driving force to do something about these things. And 35 years ago there weren't any court decisions holding that yes, the Indian tribes here in the Pacific Northwest have an enforceable treaty right to the fisheries resources of the area, which gives them the right to insist on habitat improvement and protection.

Recently, for those of you who don't know, Judge Edward Rafeedi of District Court in California, here by special assignment, ruled that the Indian treaty rights to take fish include the right to take shellfish. This case started 25 years ago, in 1970, and it was one of the first cases I worked on. I never dreamed that 25 years later, now 3 inches shorter and 50 pounds heavier, I would still be working on the case. But here we are. And it's important to know what happened.

When we started the case, we said the tribes have a right to take all fish, including shellfish, and they have a right to have the environment and the habitat protected. That became way too complicated way too fast. For one thing, all the lawyers thought all fish were alike. So why did we have to worry about little details like the way they spawn and the way they migrate, and so on? We were quickly set straight by the scientists on that.

So we agreed to set aside everything but anadromous fish and deal with them first—with salmon and steelhead. That decision was confirmed by Judge George Boldt in 1974. You often hear of the Boldt decision named after him, holding that yes, the treaties were good law; yes, the treaties overrode any state law to the contrary; and yes, the Indians had a right to take 50 percent of the harvestable fish. We thought a lot about shellfish and tidelands in those days, but we had our hands full dealing with anadromous fish. Eventually we had to deal with herring, and then we had to deal with halibut. And shellfish kind of got put on the back burner.

We also dealt with the habitat protection issue, and another judge assigned to this same case, Judge William Orrick of San Francisco, ruled in 1981 that the tribes' treaty rights included the right to have fish to harvest, in other words, a right to habitat protection. The Ninth Circuit Court, in maneuvers that only lawyers would love, issued several different opinions. The Court finally vacated the District Court order on the grounds that it was premature, in that the tribes had not presented a specific case that they wanted relief on. The case was remanded to the district court. The tribes have, since that time, preferred to keep that as the proverbial shotgun behind the door, to be brought out if necessary. We hope now that the tribe's common interests with other citizens in protecting habitat will lead to cooperative efforts. But that shotgun is still there, and it's important to remember that in the context of the most recent ruling, dated December 20, 1994, wherein Judge Rafeedi held unequivocally that yes, shellfish are within the treaty right; yes, the tribes have a right to harvest them. And that includes harvesting on so-called private property.

As scientists, you need to know that the tribes have already entered into a cooperative agreement with the state of Washington and the federal government to protect the public health. As we all know, shellfish seem to be prone to a number of problems, from effects of failing septic tank systems—of which there appear to be way too many around the Sound—to natural phenomena. The tribes will be relying on scientists and asking them more and more to assist in those problems.

In addition, the court held that the tribes' right, as I said, extended to so-called private property. In that case, we got into many of the issues that Bill Dewey has mentioned as to what is or isn't cultivating. Therein lie some important ideas for scientists and technicians.

What did Judge Rafeedi hold, exactly? Well, he went on for about 30 pages on this, so it's difficult to find a few excerpts of what is or isn't cultivation, and what that does or doesn't mean in terms of our current law. But basically he said as follows: "The court interprets the term 'staked and cultivated' as the terms were defined and used in the shellfishing industry at, or before, treaty times." That's 1854, 1855.

So put out of your head whatever you as a scientist think they mean today, and go back to 1854 and 1855.

The judge continues: "At treaty times, the term 'cultivate' was defined in a shellfish context as an activity occurring only on artificial beds. In addition, consistent with the virtually uniform body of state statutes and common law, the activities of staking and cultivating occurred only on artificial beds." And I should have mentioned, for those of you who aren't familiar with the treaty, it says the Indians have the right to fish as usual on the custom grounds and stations—provided, however, they not take shellfish from lands staked or cultivated by citizens. It's called the shellfish proviso. That's where the words "staked" and "cultivated" become very important.

The judge continues: "When the parties used these terms in the shellfish proviso, they intended only to exclude Indians from artificial or planted shellfish beds. They neither contemplated nor desired that the Indians would be excluded from natural shellfish beds. Therefore, the words 'any beds staked or cultivated by citizens' describe artificial shellfish beds created by private citizens. Moreover, at treaty times, artificial beds contained shellfish deposited for either growing or storage purposes and were surrounded by stakes or other markers to the extent that they did not interfere with navigation. Thus, clearly, as has been explained, the intervener growers' farms, which are artificial beds as herein described, are staked or cultivated, as that clause has been interpreted by the court. Such beds are not subject to fishing by the tribes, except to the extent that natural clam beds may be subjacent to the staked or cultivated shellfish beds, as explained below. Finally, it is also clear that the intervener private property owners' natural beds are not staked or cultivated. Thus, natural beds, if any, located on privately owned tidelands are part of the tribal fishery."

He goes on for some more pages on these issues, again quoting from scientific journals of the times and from legal authorities of the times, all on the basic point that, as the tribes agreed, where there is cultivation—as that term was used in 1854 and 1855—the treaty right does not obtain, but in other cases it does.

What does this all mean when we couple it with the environmental right (which we usually discuss as Phase 2, because it was separate from Phase 1)? What this means is that you will see the tribes increasingly concerned with the science of shellfish health and safety and pollution. The tribes are happy that we have the Puget Sound Water Quality Authority and that we have the environmental laws we do. But they will insist that their treaty right be recognized. This is a supreme right under the Constitution—don't forget the supremacy clause of the Constitution. They will insist that steps be taken to improve the general shellfish health of the Puget Sound area.

They're looking forward to this being cooperative, and I'm sure that there are many people of good will who want to join in this. We all have a lot to gain from stopping pollution, from improving sewage treatment around the Sound, from stopping septic tank failures, and so on. But we now have an additional legal weapon that should excite you all; namely, that there is a federal treaty right that is, in my view, being violated if pollution is not stopped, and if ways are not found to protect the shellfish resource.

I'm going to stop early because I've been trained as a lawyer speaking before courts. Most appellate courts now, including the U.S. Supreme Court, have a series of lights that come on when your time is up. You're told in the U.S. Supreme Court that when the red light comes up, shut up right then, or else you lose your case. So I'm going to stop before any lights come on. Thank you.

Fagergren: Judith Freeman now will speak from the state's perspective. Then with luck we'll have time at the end to answer questions on this subject in general.

Judith Freeman, Deputy Director, Washington Department of Fish and Wildlife:

Thank you. I'd first like to say that I am not an attorney. While I'm going to be talking to some extent about Judge Rafeedi's ruling, I'm going to be talking about it in terms of the questions it raises for the Department of Fish and Wildlife, which views itself as the manager of the resource, and what the implications are to us and to the state of Washington as we move forward with implementation.

First of all, I'd like to talk about where we are in this process. When the judge issued his ruling, which gave the tribes 50 percent of all the shellfish, he asked the parties to come back by January 31 with an implementation plan. While the judge went through many pages, as Mason pointed out, talking about the difference between cultivated and natural beds, he didn't spend any time at all talking about how we're going to manage these resources cooperatively, how we're going to determine what allocations go where. He basically left that to us. That wasn't a surprise. Typically, a ruling raises more questions than you started with. It may give you a couple more sidebars, but basically you have a lot more questions than you did before.

The first task before us is to file this implementation plan by January 31, unless the parties all agree we're not going to make that deadline, in which case we can go and probably buy a little more time. We're hoping that we can meet this deadline. We're not viewing this implementation plan as something that's will be complete with every detail about how we're going to proceed, but rather, as something that provides a framework for how we're going to communicate. Perhaps the plan will start to build the definition of artificial versus natural beds. Then the real work will start, which will be cooperative management plans for all species—not only the intertidal species, but also the subtidal species.

I'm going to limit my discussion to intertidal issues because I think that's the main focus of this group. I don't know how many of you followed all the editorials that were in the paper as a result of this ruling, but just about every major paper in the state ran an editorial on it. These took a wide range of positions, from "Protect private land," to "The Indians were the original property holders." But in most of those editorials the bottom line was: We have to work this out; we have to work together; we can all benefit; and the resource can benefit from our working together. The Department of Fish and Wildlife has a history of working with the tribes. It's not a history that goes back many decades, but it does go back more than one. We're very proud of that relationship, and we intend to maintain it as we move through this process.

Now I'm just going to throw out questions for you. These are the kinds of big issues we're grappling with as we consider the fate of 50 percent of the resource on all lands, regardless of ownership of those lands. Has the judge, then, erased all boundaries on the tidelands? Is there now no distinction between one piece of property and another? And if we talk about 50 percent, is it 50 percent inch by inch all around Puget Sound; is it 50 percent by some artificial beach—this state park, that piece of private property, this piece of public property? Those are all things we're going to have to work on.

When the treaties were signed, there was no private property in the form of tidelands. There was no private resource in terms of tidelands. As Mason said, the court tries to interpret the treaty based on what it probably meant at the time it was signed. One could say, well, at the time of the signing, there was no private property, there were no private shellfish resources—that would be one interpretation. Since the signing of that treaty, however, there have been decisions in several state cases that have held that if you own the private tideland, you also own the resource that's on it. The state, in fact, has viewed the resource in that manner. I'm not going to get into the issue of natural versus artificial beds, just the ownership issue: If you own the tideland, do you own the clams? We have always operated under the premise that yes, you do; if you own that tideland, you own the clams, you own the oysters, you own everything that's on it.

Well, the new decision throws this view into question. If, in fact, the tribes are entitled to 50 percent of all the resource, who now owns that resource? Furthermore, it's not 50 percent of the resource. It's actually 50 percent of the *harvestable amount* of the resource. So that means a certain amount of resource that must stay on the bed. We perform biological assessments as we manage public beaches around Puget Sound—and in most instances, we do that cooperatively with the tribes, because we do have some interim management plans with several of the tribes. But when we manage with that conservation base, we must leave 50 percent to 75 percent of that resource on the beach. So only 25 percent to 50 percent of the resource, then, remains for harvest. Of that 25 percent to 50 percent, half would go to the tribes. Half would go to the public, if it's a public beach; to the private landowner if it's a private beach. Remember, I'm talking about this with question marks at the end.

So does the public now own that conservation base? And does the public now own that tribal share? So has the private landowner gone from owning 100 percent of that resource down to owning 12.5 percent to 25 percent of that resource? Whose responsibility is it to manage that resource? Is it every individual private property owner's responsibility to manage it, or does it now become the responsibility of the state to do so in cooperation with the tribes?

These are the main questions that come up. So, who owns the shellfish becomes the big issue. We're sitting here and saying, well, we don't know *anything* about the resource that's on private lands. We've never paid any attention to it. We've never thought that was our issue. We've never monitored what was harvested from it. I believe we now do require people who harvest on private land to have a license, unless they are the owner or the owner's immediate family. A lot of you may not know that, but it's something you might want to remember the next time you go to your neighbor's beach. We live on the waterfront, but we don't own the tidelands. If we go down to harvest we have a neighbor who does allow us occasionally to dig some clams. Of course, I ask first. And we have our little tags on when we go down.

So who owns the shellfish? Who determines what's harvestable? Does the state do it in cooperation with the tribes? Do the tribes do it with individual landowners? Who actually will do that? I think it's likely that it's going to be something that would fall into the purview of the state and the tribes. But those are all things that we're going to be working on.

With many things, as with salmon, the rules the are set down very simply, and the implementation becomes very complex. So what is a beach? Who owns it? Who owns the resource? Who's going to manage it? And so forth. Those are the questions we have to deal with.

On the other side, the state will have some goals and objectives. What does the state want to achieve in the implementation plan, and in the development of this umbrella plan, the subsequent implementation plan, and the subsequent separate management plan? And while that also is still under discussion, we hope to approach this not with the attitude of, how quickly can we get through this? Rather we want to consider where we want to be 10 years from now, and what is in the best interest of the long-term cooperative management of shellfish in Washington state. Let's put a system into place that's efficient, that's effective, that's not cost prohibitive, that doesn't lock us into the salmon regime, where we have to count every last single salmon in order to determine the allocation. Let's figure out, between the state and the tribes, what kind of a system we can put into place that would be workable and not be so intricate that we lose sight of what we're trying to do, which is to preserve, enhance, and make use of the shellfish resources. So that's an important consideration.

Continued opportunity for recreational harvest is another important issue for the state. We feel that we have a responsibility to provide that opportunity. With most tidelands in the state in private ownership, it's been an uphill battle for us to provide enough resource for recreational harvesters. So we hope to ensure that people who don't happen to live on the water or have their own piece of tideland will continue to have a place to harvest shellfish.

Those, generally, are the main goals; there will be other smaller ones. As far as what's happened since the ruling was issued just a few days before Christmas, we have had a couple of meetings of the state caucus. The state caucus is made up of the Department of Fish and Wildlife, Natural Resources, the Department of Health, Parks, and the Attorney General's Office. The tribes have had meetings themselves. The parties have not gotten together at this point. The first meeting is to take place next week. Then we will be reviewing a draft the tribes have worked on, a draft of this umbrella framework. Within that, we would expect to start to see the principles that we've used in other cooperative arenas—advance notice of regulations; everybody knows what's going on; no harvest occurs in the absence of management plans—so that orderly fisheries can occur in all areas.

We'll be meeting with them next week. In addition to that, of course, the question is out there about whether the state's going to appeal. Furthermore, as Mason mentioned, there are three other parties that have intervened as defendants in this suit, and all of them may chose to appeal the decision. Once again, I

want to remind you that I'm not an attorney, although working in fisheries does expose you to legal issues on a regular basis.

The most recent development—and I'll close on this—is that the governor and the leadership of the legislature has just sent a letter to all the tribal leaders, under attorney general letterhead, asking that we sit down and make an attempt to settle this. There is a concern that the appeals will go on for the next 10 years—or who knows how long—and that the cloud under which we would function while these appeals are going would not be good for our relationships, nor for the resource. That letter went out late yesterday, so the attorney general and the governor will be waiting to hear from the tribes to see if we can't sit down once again and try to come to an overall settlement. As you know, we have tried that in the past and have not succeeded. But it certainly is clear that we have a few more sidebars now than we did six months or a year ago. Basically, that's where we are now. I'm sure some of you will have questions for us later.

Fagergren: We have a few minutes for general questions of any of the panelists.

Q: It occurs to me that the knee-jerk reaction of dividing a resource by geography, or by number of clams, might not be the best way to do it. And I think that one opportunity that may exist is for some kind of joint venture between tribes and community. I was wondering if the panel would like to comment on the opportunities.

Dewey: As far as the edict is concerned, it's difficult for us. We try as businessmen to maximize profits for our businesses out in the tideland. To enter into a joint venture with the tribes to manage fish is a different matter.

Fagergren: Anybody else want to respond to that?

Morisset: I can appreciate that, and I think the tribes do, too. You got to understand that for the tribes, the major victory here is in free-swimming and subtidal species, and not the kind of critters that Mr. Dewey raises. And the tribes are concerned about getting their share of *those* species, which are commercially viable, rather than running around arguing about the exact nature of specific pieces of property that Taylor United or some other grower might have. Maybe I'm agreeing, but I don't know that a joint venture would be worth pursuing. The tribes are very concerned when it comes to intertidal species, for ceremonial subsistence purposes. And those kinds of things, I think, can be accommodated, where necessary, on growers' property that is being used now where there's a natural lay of some kind, and on private tidelands, without disrupting those tidelands. I think that we need cooperative agreements there; but I don't know about joint ventures as a business matter, as a generalization—I'm not sure that would work, either.

Fagergren: I think there are opportunities for enhancement of beaches that we've all talked about for a long time. From my perspective, the development of techniques and protective mechanisms, as well as enhancing species, is something that could be a benefit to the tribes and to the state. Input from the growers, who really know the areas, could be helpful here. So I see sort of a compromise position there, I guess.

[**Question** regarding private landowners, monetary liability, and the ability to manage]

Freeman: I'd like to point out that I'm not an attorney. In the judge's ruling, he does suggest that property owners who are affected by the ruling might look to the state of Washington for recourse, in having sold those lands without a clear indication of what potential restriction might have been on the title. The attorneys are discussing what might be the outcome of those kinds of cases. But the continuation of that question is, however: What was the *federal* responsibility in terms of those tidelands? There is a lot

of discussion about the fact that when this state became a state, it was very clear that the intention of the territory, once it became a state, was to start selling those tidelands immediately. And there was no action or response on the part of the federal government to that intent. So the open question is, if the state is sued on the tidal issue, is the state then going to turn around and sue the federal government? That is the question.

Morisset: The more immediate legal problem is, what about title insurance companies who may be right in the middle of this, before it ever gets to suing the state or the feds? I don't know the answer to those things.

Freeman: The title companies are actually interveners in the lawsuit.

Question: What about shellfish that have been introduced into the area since the treaties? Do treaty rights extend to those?

Morisset: Judge Boldt ruled, about 100 years ago, that introduced species didn't make any difference. That was the question of dealing with fish hatcheries, and so on, when the argument was made that—well, these fish weren't here then. Judge Rafeedi basically said, that's the same thing here, we can't argue about what was or wasn't here, because you get into terrible problems of how certain species were destroyed by introduced species—how some species were here, and then very strange, bizarre worms came, in the holes of boats. This is fascinating stuff—I just can't remember it. But basically he said, we can't get into that battle, so whatever is here is fair game. And whatever may be here in the future is fair game.

Q: If there are historical inaccuracies in the decision, is that a basis for appeal?

Morisset: Appeals can involve both questions of law and questions of fact. In a case like this, the question as to the court's findings of fact will probably be whether or not they're supported by substantial evidence. He has already made determinations as to what the facts are, based on competing views of historians, anthropologists, economists, and endless scientists that testified in this case. So an appellate court would have to find that there was a lack of substantial evidence to support his conclusions. That doesn't mean that they won't say, well, yeah, there's a difference of opinion, and we might believe "B," but we can't say that it's wrong for him to have believed "A." So unless there's some really egregious error in historical findings, I can't see a reversal on that ground.

Fagergren: I want to thank you for attending. Please help me thank all of the panelists; I think it was a great discussion.

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PUGET SOUND

RESEARCH '95

SESSION 4B

WATERSHED COMMUNITY-BASED PLANNING

Session Chair:

Katherine Baril

Washington State University Cooperative Extension

PANEL: WATERSHED COMMUNITY-BASED PLANNING

CHAIR

Katherine Baril, Washington State University Cooperative Extension

PANELISTS

Betsy Geist, Antioch University
Linda Hardesty, Washington State University
Victoria Sturtevant, Southern Oregon State College
Margaret Shannon, University of Washington

Katherine Baril, Washington State University Cooperative Extension:

I work with WSU Cooperative Extension. I'm out on the Olympic Peninsula in Port Townsend. I've spent about 15 years doing conflict mediation and resolution on the spotted owl, salmon, and now collaborative community resource issues.

I had a chance to propose this panel. I've come to many of these workshops, so I set a couple of groundrules for myself. I wanted this to be provocative, thought-stimulating and on the cutting edge, because I am tired of seeing slides in 10-point type of things I don't understand.

And I also wanted to underscore that technology and science are not merely done with a microscope; they are done with our brains. It's a people issue, not just a science issue. And that just as technology is developing stream restoration and sediment technology, it's also developing in the *human* sciences. It's best when we can all come together, on a community level, to solve some of our social problems.

And these are social and political problems, not technical problems. I would refer you to Dr. Nancy Hansen's study evaluating 10 years in the Puget Sound Water Quality Authority, in which she determined that watershed plans focused too much on the science and underestimated the community value and political aspects of these issues.

So this panel is about the new technology that is developing, the sociology of watershed planning. Our speakers for today come not just from Puget Sound, but also from the Columbia River bio-region of the western United States. Some are working in the Sierra Nevadas. Some have worked in the Montana coal fields. Some have worked in whole-systems work in China. Some have done range systems. What we hoped to bring you with this diversity is a chance to step back from the trenches and begin to see the landscape in which we are working. And that landscape is broader than just water. It's about forestry. It's about economic development. It's about feminization of poverty in rural communities. It's about how we come together as a people to solve our local problems.

One of my favorite moments at the Clinton Forest Summit was when a fellow from the Plum Creek Timber Company brought a brand new, off-the-computer Landsat photograph of my backyard, the Duckabush River on the Olympic Peninsula. For the last 15 years, I had been trying to pull together timber people, environmentalists, and foresters, to talk about a certain elk herd that goes from the glaciers of the Olympic Mountains to the salt water on the Hood Canal, coming down the Duckabush River. For 15 years, we had made no progress on this watershed issue. People denied this herd existed. They denied they used these paths. There was disagreement about who owned them. There was just no common ground at all.

This one landsat photograph was held up to President Clinton as an example of the technology we will use to solve our problems. The satellite happened to have taken a photograph of the Duckabush River. There was the elk trail of trampled vegetation coming from the top of the mountains to the saltmarsh. We could see it on the photograph. We said, "We can see it, and now we can begin to manage for it."

I think it is our ability to see the landscape that we are working on that will allow us to take advantage of the opportunities for massive change. When you've got a lot of cauldrons boiling, and you've got a lot

of emotions moving, those people who can see the landscape—see the big picture—are the ones who can take advantage of the fertility of that biological system. So we're asking you today to do some spawning with us. We're going to have fun, and we hope to create some new genes here today.

Our first speaker is going to be Betsy Geist. She's a professor at Antioch University in downtown Seattle and teaches a "Sense of Place" class by taking graduate students to Pioneer Square and newer parts of downtown Seattle. She's a gardener who keeps her backyard as her sense of place, but she's worked in China, where she worked on whole-systems design. She talks about ways natural systems can be used as metaphors for human dynamics.

The next speaker is Linda Hardesty. She's a professor in Range Management at Washington State University. She has done a lot of work on eastern Washington and range wildlife issues. She has recently returned from a Governor's Council study on grassroots resource models and ways communities can come together.

Dr. Vicki Sturtevant is from Southern Oregon State College in Ashland, Oregon. She has been working for the Applegate Partnership and the Rogue River Institute. She brings experience from the Kentucky coal mines and shows us how we can learn from the way the mining communities faced their problems.

And last will be the person to blow our minds, Dr. Maggie Shannon of the University of Washington. Dr. Shannon is chair of the Institute for Forestry Policy at the University of Washington. Some of you may have joined us for a class yesterday on natural resource law and policy. Both Dr. Sturtevant and Dr. Shannon were involved in President Clinton's Forest Plan proposal under Forest Service work.

Betty Geist, Antioch University:

I teach in a program called Whole Systems Design, and my real fascination is the assumptions we use to construct our sense of reality. These assumptions guide our behavior, although we're mostly unaware of them. In the introduction, Katherine said I was going to talk about decision-making and organizations, and I have done quite a bit of work in that area. But, what I'm really fascinated with is the extent to which a particular paradigm has infiltrated all aspects of human activity in our western culture. And that I would call the commercial paradigm.

I'm not at all anti-business. I think any culture has to have trade, has to have business. But my sense is that the business model is not an appropriate model for all human relationships, and all relationships period. It's been very interesting over the last 20 years to see how much that has affected all that we do. I remember a professor I had in graduate school talking about exchange theory. He was very excited about this because you could talk about all relationships in terms of exchange. This even applied to your lovers—you do something for me, and I'll do something for you. Everything was trade. This view turns *everything* into a commodity.

I think it's pretty common these days to decry the materialism of the West. But it's only recently that I've been struck by the extent to which that materialism has infiltrated all of our thinking. As a result all decision-making, all organizations, now take on the tenor of a profit-making business. I suspect most of you work in non-profit or government agencies, as I do. We're all supposed to follow the total-quality movement now, or whatever the latest management thing is. It's not that those aren't bringing some interesting ideas to bear on the role of organizations. But they're all based on a model that looks at profit. They all come from a model that is based on the assumption that somebody's got something to sell, and somebody wants to buy it—whether that's knowledge, or a product, or a commodity.

In my university for instance, we do the budget process first, and the academic planning follows that. That's fine if what you're trying to do is come up with a profit at the end—or, for non-profits, a balanced budget. I think fiscal responsibility is perfectly O.K., but if "the bottom line" becomes *the* purpose, then what you end up with is ..what? You will not have a school; you'll have something else. In any case, your organization won't be what it was meant to be.

I've been playing around with two themes for this talk, phrases that kept coming up for me. One was, "You can't get there from here." It's from the well known story of a traveler asking for directions in New England and being told, "No, sorry, you can't get there from here." Well, I think we are trying to do some things in our society that you can't get to from a particular approach.

That brings me to the other phrase. Louis Sullivan, the 19th-century architect, coined the phrase, "Form always follows function." I think that's really true. The form needs to follow the function. I think we need to be very clear on what our intention is, and we need to let our intention dictate the form our efforts take. But more than that, I think it's important to realize that the way in which we go about doing things will also dictate what can happen—in other words, function can follow form. It's recursive. And once you take a certain approach, you may not be able to do something else.

Now for some examples. I hope I don't offend anybody here. I've been involved in a group called Sustainable Seattle. Is this familiar to anybody in the room? It's been a wonderful initiative. It started maybe four years ago as a non-organization, pointedly—people saying we don't want to be an organization; we want to be just people coming together to look at sustainability issues for the city of Seattle. Over the course of several years, probably 400 people got involved at various stages in a discussion about what would it mean for Seattle as a city to be sustainable.

In the course of our discussions, it occurred to people that it was important to find and identify indicators of sustainability. Otherwise, our efforts would be totally ungrounded. We began to generate indicators of sustainability. We identified hundreds, then decided to research 40 of these that could be tracked over time. The first 20 were researched in a publication that came out almost two years ago now. The second 20 have just been researched, and the report will be out this next year. If you haven't seen it, I'd encourage you to get hold of a copy. It's really interesting stuff.

Beyond the two reports, the group's efforts have led to an incredible exchange of ideas among those 400 people and their friends and family. That's all great. But what's happening now is there's a board of directors. I just got a memo this week saying there's going to be a big organizational meeting to talk about the P.R. committee and some other things that are happening. The group is turning into an organization, there's no question about it. In fact, the memo said "the organization." What they're asking themselves is, "How do we structure ourselves to do our work?"

What they're doing—and at this point, I'm going to say "they" because I'm not feeling in alignment with this part of it—is what's very natural to do. They're creating an organization so that they can have a P.R. committee, so press releases can be given to the newspapers. They're going to have an education committee, so that workshops can be given to the citizens. And what they've created is the expert model all over again. And now what happens is, the wisdom that was generated by the exchange of ideas among 400 people has become a commodity that will, in effect, be sold.

Now, this *is* a way to get information out, there's no question about it. The information will be spread in another way. Press releases may be good because as a result of them articles will be placed, on the topic of sustainability. They'll be in all the places that you would hope they would be. But I'd like to raise a question: Is that what's really important? And can we get to the kind of community dialogue we want if the information comes from the outside and is given to the citizens?

When I teach I do not follow the model of feeding the baby birds. I like the model of education that goes back to the root of the word, which means *to educe*, to draw forth. In education, what I'm hoping to do with my graduate students is draw something forth. In our work in communities, I'd like to see us draw forth the wisdom of the people who live there. I don't mean to downplay the technical expertise you all have, because we really need that to back things up. But if we're going to get people involved in understanding what may be called natural resources, or place, or their surroundings, or their relationships in community, we need *to educe* from them their sense of those relationships, not as commodities, not as something to be bought or sold. The knowledge will come through their own experience and their own *knowing*, and not from something that's been fed to them or sold to them.

I do find the evolution of the Sustainable Seattle movement of some concern. My argument about the group's change in direction is a hard one to make, because on the face of it, the change looks very natural

and very appropriate. But I want to raise that experience as something to think about as we go about creating dialogue in communities about planning and decision-making. How do we do that? What are we really trying to do? What do we really expect to happen? Because you can't necessarily get there from here.

I recently came across a quotation I really like. It comes from Aldo Leopold and was written at the turn of the century: "We abuse land because we regard it as a commodity, belonging to us. When we see land as a community, to which we belong, we may begin to use it with love and respect." My sense is that what we're talking about are different kinds of relationships. When we talk about water, watersheds—our relationship to that, and the relationship of other resources in the area to that—it is not one of commodities. Maybe it's family. I'm not sure. But I'd like to suggest that we begin to look for different models or different metaphors, because I think we really need them.

Here is another quotation I found just in the last week, this one by Amory Lovins: "Public discourse suffers because our society has mechanisms only for resolving conflicting interests, not conflicting views of reality." My sense is increasingly that we have truly conflicting views of reality, conflicting paradigms that we're working with. And you can't talk across those lines, using our current technologies. We have to develop some ways of changing that.

Linda Hardesty, Washington State University:

Betsy set me up, and she didn't even know it. First of all, I'm used to being on programs where I'm the minority in terms of gender. But in this case, I'm here in the minority in terms of my disciplinary background, because I'm one of those 10-point-type slide people, but I use 14-point.

But I'm used to talking about everything in terms of confidence intervals and probabilities. Trained as a hard scientist, I've worked as a practicing forester, a wildlife biologist, and as a range scientist. I've practiced these professions in different continents around the world, and I have a very rigorously trained scientific viewpoint of the world. But because I was a manager for so many years, and responsible not only for commodities, but also for the status of resources, I learned that the scientific training I had really didn't do me a whole lot of good for getting things done. It showed me what *should* be done but it didn't give me a clue as to how to do it.

The reason I'm giving you this background is, the points I want to make today are not based in any kind of social science theory. They come from my own innate knowledge of the landscape, of trying to get something done on the ground. These are things I've learned through trial and error. And now that I've been teaching for a few years, I've been able to draw not only on my own experience but also on that of my students and my colleagues.

So I'm going to condense this. It may not agree with your experience. If any of it does, maybe it'll be a little reassuring to you as you recognize some your own observations.

The first point that I want to make is, I had to learn to determine what is the common interest. In the past, in the '70s and the '60s when you worked for a government agency, you didn't have to worry about what was the common interest. Your mission was given to you, your authority was given to you, and you went at it. Here's what you have to accomplish this year, here's your truck, here's a budget—go. It's a wonderful way to live, but you don't really know what you're doing. But after a while when you're out in camp at night by yourself, you start wondering why you are doing this and whether it is making any difference. Those questions start to trouble you.

I worked overseas for a number of years, and when I came back, I came to Washington State University. I wanted to implement some of the land-use practices I'd seen overseas, which were much more integrated than our approach has been in the United States in the past century. People kept telling me, no, that's not an appropriate technology for Washington. The technology was agriforestry, a means of integrating the production of trees with agriculture.

But I felt it certainly must be. So I decided to do a survey and get some data. I thought I'd get comfortable, get the kind of tools that I could use to convince people. So one of my students and I

designed a survey of private forest land owners in the state of Washington, to find out more about the resource that they manage, why they manage it, and what they're doing. Maybe they're doing some of this stuff but they're not calling it agriforestry.

A year and a half later, we found that more than half of the private land owners that we surveyed in 12 different counties, in three regions of Washington, were indeed practicing at least one agriforestry technique—many of them more than one. They didn't consider it an accepted practice, so they kept kind of quiet about it. They saw it as sort of an illicit thing. You don't go to your extension agent and ask how long you can keep your sheep in an orchard—because putting sheep in an orchard is not a real cool thing to do.

So we started to build a database about these people that would justify this program. I'd like to tell you a bit about the data, because I think it can help us answer the two crucial questions that lead us to the areas of common interest in resource issues. The first is, what are people's decision criteria? And the second is, what's the demographic situation? These questions are related.

The average age of the agriforesters that we surveyed in Washington was 59. Their main reason for owning and managing land was to pass it along to their children. The average 59-year-old has adult children. If they're not making their living on or near the land, it's unlikely that they're going to do that when the time came for their old parents to turn the land over to them. So we see a demographic shift coming up.

And if any of you have read Ivan Doig's *Montana Trilogy*, its last volume, *Ride With Me, Mariah Montana*, crystallizes that in a lovely way. And because the idea comes through a novel it's not too threatening and not too academic. It's this idea that here you've nurtured this land and this resource so you can bestow it upon the next generation. But the next generation lives in Boise and is working as an electrician and really doesn't want to go out there and mess with it because there are snakes out there. The values and the attitudes toward the land have changed.

What I tell landowners is, focus on your grandkids, because they might still be salvageable. That's kind of tongue-in-cheek, but do we have to consider this demographic change. Another demographic change we have is the immigration into rural areas of people who have different values. Newcomers can have a very different image of the land. What to me is a beautiful landscape may be very threatening to them.

We've got a lot of students right now coming from the Midwest and from the East Coast, and they're really frightened when we go on a field trip. Last year I had a student get lost within a quarter-mile of the pick-up on a field trip. It took a long time to find her, and when we found her she was frightened, shaking, and in tears, because she thought she was lost. We used to have students who had grown up in the wilderness. They would take off fishing for a week with nothing but fish line and cornmeal in their backpack. We're not getting those kinds of students anymore. The students we get perceive the land as threatening. Even though they want to work on the land, and they're investing their time and effort to study these things, they're not comfortable with that resource.

I found this in the survey data: One of the most important incentives for our landowners to use different practices is aesthetic values. Now what I want to do is design a study to find out what they consider aesthetically pleasing. I live in north Idaho, and what many people find aesthetically pleasing I find a little bit disturbing sometimes. You've probably all found this in your neighborhoods, as well. But aesthetics is a powerful incentive. If I want to market, for example, soil conservation practices, I can probably market those practices in terms of benefits to wildlife habitat or in terms of aesthetic benefits more easily than I can market them in terms of soil conservation.

So now we want to find out, what is aesthetically pleasing? Aesthetics are important in decision-making. So are the generational and family concerns I mentioned earlier. But neither one of these can be quantified with data. You can't go out and measure it. You can't sit in your office and say, we'll design a policy or a regulation that will require people to do these things because it's in the common interest of the community to conserve resources.

I'm a great believer in carrots rather than sticks. We know what the carrots are now, in some sense, what we might use to motivate these landowners. Now we just have to find out how to use them. But because the program I'm designing now probably won't be fully operational for 10 years we have to remember we'll be dealing with a different audience then than we would be dealing with now.

Another observation that I want to talk about is the fact that order emerges only after the fact. I was involved in the first Grazing Environmental Impact Statement that was ever done in the '70s. It resulted from a lawsuit, Natural Resources Defense Council vs. Rogers Morton and the Department of Interior. If you're at all involved in range issues, you know this was a landmark case. I spent a year and a half going to public meetings that would break down into fist fights in the BLM offices. I went to Cattlemen's Association meetings where people were all sure they were going to go out of business. Some people I knew actually sold out in anticipation of the demise of the range livestock industry.

It's much the same rhetoric we're hearing today about Range Reform '94, exactly 20 years later. When I'm teaching History of Range Policy, and I talk about that period of time, I can talk about it legislatively, in terms of what happened and why. But I can also talk about it from personal experience—what happened to the people in the community that I lived in and to the communities that I worked with. At the time, I worked with more than 400 ranchers in 10 counties in Idaho. They were intimately involved with this issue. Now that I look back at it, it's relatively clear to me what happened and why, and how the process developed. But at the time, we really didn't know.

I used to look at my friends in the Forest Service and sigh, and think, oh I should try to get on with the Forest Service; they've really got their stuff together. Well, those of you who have been involved in Forest Service issues lately know that having it together runs in cycles, and they're kind of on the down side right now. But at the time, they were really right on top of things.

The point is that there is order even to the messiest process. You just can't see the order when you're in the middle of it. And if you look back, those lessons become very clear. I'm much more interested in listening to the old-timers than I used to be—partly because I'm getting to *be* one, but partly because I can ask people now: What are the patterns?

We're going through another round of budget cuts at our university. I watch the more senior faculty. What kinds of proposals do they get upset about? And what kinds of proposals are water off a duck's back? "Oh, we went through this in 1958, and we went through this again in 1964, and this is how these things happen." So I'm starting to find my own sense of pattern as well. And although the patterns don't completely constrain you, it's useful to look back and discover those patterns.

This brings me to my last point. We talk a lot about interdisciplinary lessons. I guess because I've crossed disciplines several times, I realize that the principles stay pretty much the same. This is true for physical scientists: gravity doesn't change depending on who you work for. There are certain finite limits to how the world works. I believe that also applies to people—human nature, human motivation. I've worked in Arab cultures. I've worked in Latin America. But I find that once you really get to know people, once you have a means of communication, it's the same process that's driving people and the same concerns. So if we can look into other areas where we have other vocabularies and other experiences, the novelty of that context may give us new insights into our own situation. Just because my brother is an engineer doesn't mean he might not have an insight that could help me. These broader contacts that we have, then, could prove to be where some of the answers are. So let's cast the net a little bit wider.

International lessons are the same as interdisciplinary lessons. It's so much easier to see something in another culture, because you are able to put aside your own blinders and defenses without feeling threatened. You see it, and you suddenly realize, oh my, this has been going on *here*. But you hadn't been able to see it. So it's like cleaning the mud off your glasses sometimes to immerse yourself in another culture—and it's something I would encourage you to do if you have that opportunity. Or even just to travel. Sometimes I travel for recreation. When I was in New Zealand last spring, I would talk with farmers. I found they had exactly the same concerns that I have about our farm in Idaho. It's very helpful to realize this isn't a small-scale problem we're dealing with. This is a global problem. It's worth the investment to try to resolve it.

I wanted to boil this down to kind of a bumper sticker message that you could take home. That message relates to Betsy's theme of "you can't get there from here." There are a lot of places in Idaho that you "can't get to from here" if you travel by conventional means. If you go by car, you can't even get from north to south Idaho a lot of times without going out of state. But if you have a small plane, or if you're a whitewater rafter, or if you're willing or able to put on your boots and hike, you can get from anywhere to anywhere in Idaho. I know because I've done transects, and I've had to do it. You can do it, but you have to be flexible about the means.

So the bumper sticker that I propose is, "Keep Your Focus on Your Ends"—on where you're going, on what you want to accomplish—and then find a way to get there. Too often we get so hung up on how we're going to do it that we forget what we really want to do. Any of you who have worked in a bureaucracy know that at the end of the year they don't really care what you've accomplished, but, my God, all these forms had better be filled out. Sometimes, we just have to remember why we're here, and what we would want to have said about us when we're gone: "She got this done, and this done." And it was because she found a way to get to there from here. Now it may have been a peculiar way of doing it. But in the end, all that really matters is that she got there.

That's my innate knowledge of social science and natural resources.

Victoria Sturtevant, Southern Oregon State College:

I'm going to talk to you today about community-based collaborative planning efforts—what works and what doesn't. I'm going to talk mostly from my experience at a case study of the Applegate Partnership, although I've been working with a number of other partnerships and studying them for the past couple of years. So I'll be talking from a broader range of partnership groups.

The Applegate Partnership is a collaborative effort. It's a multi-party, multi-agency, multi-ownership, multi-problem group. Two years ago, some people got together who had been working very hard trying to plan and basically fight agencies that were managing land in a 500,000 acre landscape area in southwest Oregon. They were tired of the deadlock, tired of getting nowhere, and they decided that they were willing to take the risk of sitting down and talking to one another. One of the first things they did was make little buttons that said, "No They." Those of you who have heard about the partnership have probably seen those "No They" buttons. They put aside their community of interest affiliations, their stakeholder constituent groups that all of them belonged to, and they agreed to put aside their occupations and get to know one another as people. It was a long, tedious process that required facilitation, and it was kind of quiet. But an agency person found out about the meetings and came in and said, "Who gave you permission to do this?" Because often the agencies have seen themselves as the third party, the neutral party, that is maximizing its numbers of enemies. It's as if they reason, if you've got lots of enemies, it means you're doing it right, because you're in the middle and everybody's upset with you.

So the people said, "Nobody gave us permission. We're doing this on our own, but you can join us." And bringing the agencies into the process conferred even more power on the partnership.

The partnership is committed to assessment, monitoring, community outreach, and community health. It's trying to promote the idea that forest health and community health are related. It's a number of people, many of whom have moved into the area from the outside, who are trying very hard to reach the community and plan for the future.

I'm going to go on to my laundry list of what works. The first thing I've observed that's very important is what I'll call community capacity. There have to be people who are already organized in some manner, who have the organizational structure, who are ready to start talking about the community, rather than themselves or their interest groups—people who are ready to move beyond the idea of private ownership. There must be a readiness, a community awareness, an understanding of the issues as being broader than just themselves. It's very useful to have a network of NGOs—non-government organizations—as well as, of course, *willing* government organizations.

The second thing that's necessary is to take time and to have a facilitator who helps with the process. It's very important to remove stereotypes and to distance yourself from those constituents. Humility, small steps, feelings, openness, field trips, food, study, assessment, focus on information rather than ideas and ideology—all of that is very important, and very time consuming. Agencies need to see themselves as facilitators, as partners, not as controllers. Everybody in the group has to take responsibility. Agencies ultimately have the responsibility for what's done on their land, but private owners also have to take responsibility for what's done on *their* land and how that contributes to the whole.

One of the things that the agencies have to do is stop waiting for the public to tell them what's wrong and start asking the public how to do things. But that can be a difficult change in approach, because then the public says, "*You're* asking *us* how to do things? This is *your* job. What's wrong with you that you don't know how to do things?" So it's not an easy shift to make, either for the agencies, who think they have all the answers, or the public, who are used to fighting against the agencies.

And that leads to the next thing that's important for what works, and that is to move from watchdog to problem-solver. Often, the public is used to being a watchdog and making sure that the industry isn't doing something wrong; there's that tone of suspicion there, rather than trust.

Often, the people who are most suspicious are environmentalists. They're very worried about being co-opted by the agencies. They want the agencies to do their own work, and they're afraid that if they sit down at the table and reach some consensus with the agencies, then they won't be able to back off and fight. One of the big questions I haven't resolved yet is whether consensus is necessary for partnerships, or whether people can back off and retain their own views and not always go along with the partnership process.

Community outreach and education are extremely important and probably some of the most difficult things for partnerships to do. For at least a year and a half, and maybe two years, it was very easy to blame the members of the Applegate Partnership for not *really* understanding their public and their community of 12,000 people—which is a fairly large community, especially when it's spread out. One of the first things that the partnership did was hire an anthropologist to do a community assessment, to find out who the people were, what the interest groups were, what the demographics were, and how things had changed. It's extremely difficult but extremely important to know the community.

One of the things that's been very successful in reaching out to the community is publishing a newsletter. In this newsletter, there's technical information that agencies have written, but there's also local information, folksy information, calendars, oral histories with old-timers, studies of the history of the area that people might be interested in. One of the things that's happened with the Applegate Partnership is that it's become a watershed council. The state of Oregon has dedicated lottery money to developing local watershed councils. One of the things that's done is gotten people in the partnership into the field to talk about streams. That's been successful, because it's been neighbor to neighbor, talking about what this stream used to be like, and what they're hoping it *will* be like. So community outreach is difficult but extremely important.

Now, I've got my list of what doesn't work. On the top of that list is mandating partnerships. It's very difficult to make a partnership happen if the community is not ready. The Applegate Partnership served as a model for the adaptive management areas that are in President Clinton's forest plan, and some of those still have a way to come. Top-down control—agencies deciding how the partnerships will work—is also impossible. Another real flaw, I think, is to have very heavily structured facilitation—to have a model that's very rigid about how the process should work. You don't want the groups to get too dependent on a particular model, particularly if it doesn't work.

Another real problem for partnerships can be notoriety—going back to that press release issue. When Interior Secretary Bruce Babbitt came to visit the Applegate Partnership on his swing up to the Forest Summit, that created some problems for the partnership. It brought notoriety, and with it raised expectations. One person in the partnership called it "performance anxiety." Everybody was expecting them to move mountains, and all they were really able to do was put rocks in buckets and carry them one place or another. People started to *expect* things from the partnership.

Another real problem is constituent obligations. When the board of the partnership was created, they wanted to have *X* number of timber people, *X* environmentalists, *X* farmers—and those people all have very strong ties to their constituents. There was a lot of suspicion and hostility from the constituents, which made it very difficult for the people at the table. Those stakeholder national and regional groups have created some tension for the people sitting at the table—particularly when the groups protest or appeal some of the actions that the partnership is trying to take. Actually, the members of the agency groups have some national and regional problems as well. Federal Advisory Committees Act raised its ugly head last spring, and agency people were told they could no longer be on the board or attend partnership meetings on a regular basis. This created a real problem, not only for the agency individuals, but also for the group, because then the group became very suspicious of the agencies, and there was a lot of scapegoating going on. When people aren't there at the table, it's very easy to blame them. As a sociologist, I know that group cohesion often is based on conflict with outsiders. It's very easy to point your finger at a person who's not there.

The solution to Federal Advisory Committees Act has been to charter advisory groups, and it's created another layer of bureaucracy, another set of meetings to go to. The other interesting thing is that these groups have been set up on the basis of—all right, we want *X* from timber, and *X* from environmental, and these people are saying, "Wait a minute, we gave up those constituency interest affiliations. We're now a community of *place*. We care more about our community than that attachment, and you're splitting us all back into these old conflicts again."

So the solution hasn't been any better. There are too many issues, which are too diffuse. The Applegate Partnership is looking at forest health. It's trying to get out sales for loggers. But it's also working on economic development. It's creating a community center and a training center. The watershed councils now take up a lot of time at the meetings. It's trying to do too many things.

And the last thing. I said one of the important things that makes partnerships work is *time*, but time is one of the things that is really working against partnerships, too—because it takes so *much* time. It's very hard to keep sitting at the table when you don't have anything to show for it. On the other hand, if you try to do things too quickly, you can get into trouble.

One of the real problems is figuring out incentives that will keep people coming. If it's that you're diminishing the number of protests against sales, and there are still sales from these outside constituency groups, then you haven't been successful. If it's personal gain, but you're really working for the good of the whole, then that motive doesn't work. If the agencies have rising expectations of you and smaller amounts of time, and you have to spend three to four to five hours a week in meetings, there's no motivation there. So it's very difficult for people to continue to put forth that kind of effort if they aren't getting the usual kinds of rewards in the business-capitalist model that we've been talking about today.

Margaret Shannon, University of Washington:

Do you hear it? Do you hear the language of these last three speakers? It's the language of the 20th-century anxiety. The language of anxiety permeates every single planning effort around natural resources and every single policy issue that we're trying to address, whether it's welfare policy, economic policy, trade policy, what-can-we-do-in-Bosnia policy, what-about-Chechnya policy. In every single arena, it's the same language.

I am a social scientist. How many of you would characterize yourself as a scientist of some sort? I want to practice my craft for you. And I'm going to have to do this with the indulgence of my colleagues and friends, for they are my data. I'm going to make only three points, and they're all based on what you have just heard. My intention is to enhance your capacity to see yourselves as social scientists as well as biophysical scientists. Because truly what it means to be a social scientist in everyday life is to be a citizen. In order to understand the world about us, we must *all* be lay social scientists. We must learn to listen to make sense of what's happening around us. Because it's our failure to do so that is the source of the language of anxiety.

You've just heard these incredible speeches that have ranged across different worlds, different ideas. I know you are trying to make sense of what you have just heard. I'm going to give you my take on that. I hope my comments will help enhance your own thinking as well.

First, is there a conflicting set of realities? This is a consistent theme among the three speakers, that there are conflicting realities. The dilemma of conflicting realities is that each reality can be viewed as an objective reality. Each reality exists out there, in and of itself, and what we should do is learn about it. Just as we can learn more about the chemical properties of water, we can learn more about our various realities. Each one is separate. Each one has its own dynamics, its own ways of understanding the world.

One model of conflicting realities suggests that the realities are mutually exclusive. Thus the problem confronting us is how to choose amongst the people in different realities. How do we determine the winners and losers? How do we reduce the protest of the losers? How do we pacify them when they lose? This model represents one way to think about society, but it is only one way, as I'm going to suggest in a moment, that is based on one assumption about our world. Perhaps another model, based on a different assumption, could help us liberate our thinking.

Rather than thinking of the world as made up of *conflicting* realities, we might think of the world as made up of *different* realities. Now, when you're dealing with different realities, you have to remember that where you sit determines where you stand. In other words, those kinds of everyday matters that we as individuals deal with are going to shape very strongly how we view the world. For me to come here this morning, I had to make sure that an 8-year-old and a 13-year-old had somebody to be at home with them because they have no school today. Now one of my choices might have been to leave them alone. And there are many people who had to make such a choice today, because they had no capacity to get child care. That strongly affects their view of the world.

We are all located differently. We all have different understandings of what it means to be affected by the actions of others, as well as the actions of the larger society—and that shapes our different realities. This model, however, suggests that realities are not mutually exclusive but compatible. Just as I had to solve my child care problem this morning, you all had to solve your own problems, and yet we can sit here and we can share the same world. Our realities are, in that sense, not conflicting and exclusive. These are two very different ways of thinking about our social world.

So I'd like to move to my second point. Linda made several very interesting observations about what it means to experience these kinds of extremely anxious moments when it is very hard to understand what's going on around us. And she suggested we should have faith because things will indeed move forward. Let me take my two models of how to think about the world and see how faith figures in each of them.

In the first model the world is an objective reality—all this is actually out there. Thus, the reason we can have faith despite the apparent chaos is that our only problem is our inability to see the order underlying it all. And thus, Linda suggests, have faith; the order is there. We will slowly come to see it, probably in retrospect. That's one way to think about the world.

A totally different way is to say, there *will* be order, because every action that we take, every day, with everything we do, will *make* order. That's a totally different vision, because it says that we must resolve to create that reality every day as we wake up. And yet, we obviously do not create it anew. Every social act has millennia of history behind it, and as it moves forward into time it creates the future as well.

What is theory? I am theorizing. You are theorizing. We have, I believe, in our segmentation of who can make theory—in our bureaucratization of the idea of who can know—we have said that theory is something only scientists can do. Yet, I think one of the reasons for the language of anxiety is that we are waiting (I assure you, we wait in vain) for the social scientists and the political scientists to make sense for us of what is going on out there.

Please wait no more. We are not going to make sense of it. But the reason is simple. Theorizing is everyday life. Rush Limbaugh provides a kind of theorizing. You cannot act unless you have theories. Theories are simply the ways in which we explain what's going on around us. Theorizing is normal, everyday life. However, we often say people are incapable of theorizing, that all they have to offer is to

tell us their wants and their needs and how best can we meet those wants and needs. This leaves us to explain to these in need that we're not going to give them what they want today, but maybe tomorrow. Doesn't this sound like the arguments over the federal and state budgets? Who gets, who loses, and how do we decide? It's a totally different model of politics from the one you heard discussed by the three participants.

A forum for politics that's based on who gets to win and who gets to lose, and how we're going to decide that, is one that, by definition, must divorce citizens from politics. We citizens become *inputs*. We become sources of information. We are not actors. Because if we are to act, that's an entirely different model of politics. You have heard here an eloquent argument for a very different political model. This model is one that is based on a collective understanding of politics. It requires each of us to take seriously the action that defines citizenship. Citizenship is action. It does not exist simply because we have been, sort of, dubbed citizens; it exists because we *act* as citizens. And if we do not act as citizens, we will be controlled by Rush Limbaugh. That's an utter non-action, to sit and listen to someone else tell us what our views are. But that is the bureaucratization of politics. That is the dilemma of expertise.

Forms for collective politics, as you have heard, take on the most fundamental shared vision of how society is organized, the commercial view. Put the commercial view, as Betsy described it earlier, into my two models of the world. The commercial view is insidious. It is based on the idea that the source of value is in its use; the fundamental idea is one of utility. And if the source of value is in use, then all you need to do in order to understand the value of a program, or a resource, or a relationship, or anything else, is simply to identify it objectively, and identify the value given to it by its use. If, however, the source of value is located in the process of valuation, then you must locate it in the politics that create valuations. You cannot, otherwise, know it outside of the processes of creating it. It's identical to thinking about what the world is—is it knowable outside the processes that create it, or must you look at the creative elements in order to think it, much less know it?

The vision of collective politics—well summarized by Vicki—suggests that it must begin with vision. Now this is not "the vision thing." This is the idea of vision that Betsy began with when she spoke of 400 people getting to know one another. That means they had to know where one another stood and imagine themselves into the future. That's what we do every day. Every day we *imagine* ourselves into the future. I, like you, make lists of what I'm going to do. I, like you, probably achieve one or two things on my list. However, it's the *process* that's important, because you have to *imagine* your day, in order to could locate yourself within it. Politics is identical. I think the reason the Contract for America has been so powerful is that it is attempting to provide this clarity of imagination.

The next element that Vicki noted was the idea of authority, which she talked about as permission. Authority is a very important part of any society, because it really stands in contrast to vigilantism. I believe this is why there was such a visceral response to Kristina Jaffrey's assertion that the perspectives of the Nazis and the Ku Klux Klan were important in thinking about the holocaust, because those are the perspectives of vigilantes, not the perspectives of power exercised with some forms of legitimacy. And that's a very different understanding of the nature of authority and permission.

So if we have bureaucratized authority, then indeed it is only those who have been so designated who can act as authorities. But if authority is something that must exist if a society is to regulate itself, then giving oneself authority is a normal opportunity of good forum politics.

The next element that comes up consistently in thinking about collective politics is the notion of what counts as knowledge. And I've said enough, I think, to illuminate that question. But in each example, there was a very difficult relationship between knowing things through the procedures by which scientists might reveal those things invisible to us, and knowing things through the common experience of finding that all of our scientific frameworks were making invisible to us the very thing we wanted to know about—and agriforestry, I think, was the clearest example of this. We were blind to agriforestry here in our country because we didn't know how to ask the right question.

The fourth thing Vicki noted is to be responsible for the outcomes, especially when they affect others. A politics of utility—the commercial model—requires no such responsibility. The fifth thing was the idea

that it was essential to have mutual problem-solving and mutual problem-diagnosis, and that this is the purpose of politics. But for that to take place we must create the public spaces, and this was her sixth point. I would raise a question for you and for her. When she stated that you cannot mandate partnerships, I understand what she means. You cannot mandate that people shall have a relationship. On the other hand, can you mandate, if you will, that a public space be opened where the discussion may take place? Is there some way that we can counter the bureaucratization of politics by trying our best to open up public spaces? I think that's what's so intriguing about the Sustainable Society program: It opened that public space. I think that's what's so interesting about the kinds of work in agricultural opportunities that Linda has been doing: It opens public space for discussions that were not possible before.

There is no doubt that we must continue to have powerful humility about ourselves, because our abilities to create a collective politics are, of course, limited by what it is we know today. We must take that humility very strongly to heart. However, I think we also need to realize that theorizing in our everyday world is simply common sense, and that the kinds of politics that have been discussed really are not all that different from trying, first, to get teenagers to listen to you, and second, to get them to contribute. Thank you.

Baril: Unfortunately, I can't avoid making a couple of comments of my own, so bear with me. I was struck by Betsy's comments on function following form. I think we may not understand yet—and it may take us another hundred years—to consider the consequences of our issues, that Sputnik happened about the same time as the first altered fish were found in the Great Lakes. This mutual dance that science and environment have done together means that we look at environmental issues under the scientific model: isolation; cause and effect; efficiency; hypothesis. The influence of the scientific model has been great. For example, the turf bureaucracies reflect the specialization of our scientific fields—that ecology is somehow different from soil, and fish and game is different from natural resources. I would suggest the fact that we sit here at a Puget Sound Water Quality Authority *Research* conference reflects that love affair we've had with science for the last four decades.

As we look at our economy, there is a triangle, and we have been consistently operating from the ecology viewpoint, but it is balanced by the community viewpoint. I've often said I would rather go into the community of Forks, not with an Environmental Impact Statement, but with a potluck dinner and a small string dance band. I think we probably need to learn those things. We all have them inside ourselves, and I hope this panel helps you free those things.

I'd like to comment, too, on Linda's point that our forums do not provide access to talk about values. She talked about demographics and age of the landowners. I live in a community that is very polarized over growth management. One of the things I have seen is that 60-year-old farmers cannot bring to the table their fear that if their land is classified as long-term sustainable agricultural, they will not be able to get the loan at the bank to cover the melt contract till they can pay their wife's health insurance policy. Where do we let those issues, those real things that make us force the decision, come to the table? We won't find answers in probability and confidence levels. They are in discussions of real-life fears, of hopes for our children, of where we are in our times of life, of how we define justice and the experience we've had in our community. Unless we give those values legitimacy at the table, we're asking people to keep 90 percent of their real motivation submerged and be caught in quicksand in our public policy.

I found Vicki's comment about consensus very interesting, because I work in conflict management and consensus work. Consensus is a process; it is not a product. It is not an agreement. It is a concerted commitment to work things out with people who are going to live and die with you. If you think that agency person is not the person you're going to work with in 10 years, you keep your fingers crossed. But if you think he's the person who's going to change the flat tire for you on a lonely country road some night, you have a different set of groundrules. And I think we need to restore that kind of interdependence in our communities. The metaphor I'd like to give you is that if you look at your watershed, at the very top of the watershed is the National Park System; a couple thousand feet down, it's the Forest Service; a couple thousand more feet down, it's the Department of Natural Resources. And you get these cross-

sections, like an oil sample of soils—agriculture, small farms, industry, finally down to the shellfish. The only things that run all the way through that cross-section of our watershed are the water and the blood of our communities. And if we do not bring communities legitimately into that process, we will continue to see the issues as isolated microcosms of the whole—and forget the fertility. We need that lifeblood.

I want to comment on Maggie's talk, too. I read a great quotation: "Government is what we do when we come together to solve public problems." In each one of the streams of Puget Sound, there used to be five different kinds of salmon. There were chinook, who came up on large, stormy floodplains, and could go from saltwater to the Elwha River—about 6,000 feet elevation in 40 miles—because they had 80-pound bodies and were great Tyee chinook salmon. And there are people like that in my community. One is a farmer. He walks into the meeting, and he fills the whole room. He is a Tyee kind of guy. And you all know people like that in your community-based projects.

We have coho. They come in, they populate the small estuaries, they spawn, they go out in 90 days and they stay in the estuary. They don't ever participate in the river's activities, but they're there if you need them. They're great low-water stream fish because they never have to go up into the rivers. And each one of you knows people like the coho. They just come for the party, they never do the dishes, and they never give money. But they're always there when you need a lot of people in the room. So you need that kind of people in your community organization.

And then there are chum. Now chum are not bashful; they will spawn in parking lots. They're the kind of fish that we put in school classrooms for kids to look at, and they're great for restoration. You can raise them in 90 days in the classroom, put them in the stream, and have all the guys with the backhoes brag, "We restored the salmon stream in three months or less." It's kind of like the instant Jello version of stream restoration. But those chum are the kind of friendly guys who are forgiving. And we need that kind of people in our community, too.

Over the 10,000 years, our natural resource system evolved to take advantage of that tremendous diversity. I hope our communities will recognize the sacredness of diversity in nature, so that we can begin to honor it in ourselves. Because it's a great lesson that nature has to teach us, as we come out reinventing for ourselves a 21st-century community that no longer sees itself with a frontier, but sees itself, as in a landsat photograph, with no place else to run.

Question and Answer Period

Q: Is this something new, or have we just gone full-circle and rediscovered it?

Baril: We're toying with that idea as well. What we're finding is that the communities know much more about town meetings than the agencies, and often the agencies are in conflict of interest with what our communities know intuitively. The dilemma I want to add to your question is, what if that community is so homogeneous that we think they'd log it all down or fish the last fish, versus a community that we think represents all interests and could reach its own conclusions. Anyone have comments?

Hardesty: Whether or not a gathering really represents the community, I'm discovering, has a lot to do with *when* you have the meeting. Because if you have a meeting during the day, you get a very different community than you do if you have the meeting at night. I worked in Utah, where there are a lot of Mormons. For them Monday night is a time to stay home with your family. So you're not going to get representative community turnout if you schedule any kind of a program on Monday night. So even what we define as community depends in part on the mechanics of how we're doing things. There are lots of people out in our communities who represent a part of the community we never see just because of the schedules that we keep. Sometimes for that reason I like to go to the grocery store at midnight. It makes me realize that the community I normally see isn't the whole thing. When we're thinking about the town hall and imagining everybody participates, it's strange to stop and think, how would we even find out who everybody *is*?

Geist: I'd like to add something to that. I think a lot of what we're trying to do is rediscover stuff we used to know but that we've lost. As a professional woman, I'm glad to have the opportunities that the changes of the last 20 years have brought. But I can see that sociologically, some very interesting things have happened as a result of those changes. When women of my generation entered the work force something we expected was that the men would naturally end up working less. Yet now we find it takes two adults to support a household, when it used to take only one wage-earner. Now what happens is that a lot of things we didn't have to buy in the past we now have to buy. And a lot of relationships that used to arise naturally in a community don't happen anymore. Now I have to *buy* child care. Now I can't garden fully the way I want to; I have to hire somebody to do some of my pruning. Now instead of going to a neighbor, people go to therapists. Aunt Bessie lives across the state, so I can't talk to her about child rearing. I mean, how many of you had to go to parenting classes, for heaven's sake? Or sex classes? I mean, we don't know how to do *any* of it anymore. The concern I have about commodification and this growing dependence on experts is that we now think we have to go to somebody else. This fits with what Maggie was saying about investing ourselves with that sense of being able to create, whether it's theories or solutions; and the need to invest our citizens with that sense as well, encouraging them, creating the context in which that kind of contribution is an expectation. I think this expectation has existed at other times in our culture. But I believe in the last 20 years it has diminished significantly.

Baril: I also want to add that unless we start seeing issues as economy, ecology *and* community, we'll end up ecologically pushing for large 10-acre parcels to preserve our open space. We'll do so without an analysis of the impact on the community. When you've got a 10-acre open space parcel, that means that a couple has a $1,900-a-month mortgage, which forces both people to work, and which forces them to own two cars. Nobody has any time to share the farm equipment or the orchard. The kids come home to an empty house. No one has time to volunteer in the community or to participate in public functions, which means we begin to pay people, as representatives, to meet during the day to talk about our interests. Unless we start doing this kind of holistic analysis, and allow legitimate interdependent issues to come to the dialogue, we risk relying on a hatchery-type, mono-culture approach. And we all know what that got us.

Q: I suggest to you that there's a whole circular process right now with our inability to use large timber companies' land. You can go anywhere now and see gates up on almost every private timber company road system that was once used for recreation. Now, they're closed; you're out. Where did it come from, the opposition? If we don't solve the situation of opposition between large timber companies, and use the lands that are available, there won't be a place for us to go.

Baril: The comment is about the loss of open and common space that has resulted from timber lands being locked up from recreational use or multi-use access.

Hardesty: I've got to take that one because we posted our farm this year for the first year. We've had problems with timber theft, and with kids going up there to drink beer and make fires, and that's a real concern to us. And that breaks my heart because places I used to hunt 20 years ago, I can't get to now. We live in an area that doesn't have a lot of public land. So now I've got two wonderful bird dogs that don't get to hunt birds. That, to me, is a painful thing, and I never thought that I'd post my own land. But that's exactly what's happening. People who are using the land don't share the values of the people who have responsibility for the land. That appears to be the problem. Locking up the land is not the only answer. We've got to make some long-term efforts to establish a different value in our watershed and the people that come here. But in the meantime, we've got to keep them from burning it down until we can get these things straightened out. I agree that's a serious question.

Q: It's not just to keep people from vandalizing the land and so on. There are a lot of landowners who very much resent the lock-up mechanisms of the environmentalists, and they post their land to get even.

Baril: I just finished a watershed plan in my area, and the plan's first recommendation is that agencies stop by people's doors and ask for permission to enter their land, because they're so concerned about not knowing when agencies are trespassing on their land.

Q: When you talk about community consensus, I get this image of a community that's been living in an area for a long time, with people who have like values and interests, as well as generations of knowledge in how an area works. But today, with our mobile population, gaining consensus seems impossible. I lived in a small community recently where a lot of people came from different directions, with different sets of values, and with different perceptions of the way things should be. Have you had any experience of overcoming that?

Sturtevant: I can speak to that. The question was, as we become a much more diverse population, as we have new people moving into rural areas who have different values about how to use those rural areas, how do you reach a consensus? In southwest Oregon, where I live, there's a great deal of in-migration as well as out-migration by people who can no longer live on the land or keep their farms. And in Oregon we have land-use planning that makes it difficult to subdivide farms. People have left, and their kids have left, and equity migrants from California and from other countries have moved in. When seeking to build consensus in such a diverse group, we have started by defining the few easy areas where people can all agree, and then we have moved from there. Often, people in partnerships say there's really about 80 percent of things in the middle that they can agree upon. It's those 10 percent at either end that are tough. But there's a range of agreement. The difficulty is when you do have to enter those areas where you can't agree. A real problem with the Applegate Partnership is most of those sitting at the table were new migrants, who had the time and the resources and the education that allowed them to spend those resources in a partnership effort. What's been interesting is that they've always known they have to involve the local people, they have to draw from the indigenous knowledge, and they have to get the community behind them, or else they've failed. Their mission is to try to inform people about why it is that they have to clean up their streams, because we're about to have the salmon listed down there. Rather than be afraid of losing your rights, ask yourself, what we can do to *restore* this dream so we *won't* have the salmon listed? Salmon are one of those 80 percent things that everybody can agree upon. We all want to have salmon. The question is, how do we get them? What we've found is, the best way to get everybody to agree is to get them on the land, rather than sit around the table and talk about what they don't agree on. When you get on the land, forest health is something, at some level, people can agree about.

Geist: I'd like to add to that. There's a technique I've used in a class I teach on experience of place that I think could be replicated in lots of different settings. That is, I ask my students to do a map of their neighborhood—and I don't give them much more instruction than that other than to say, "put anything on the map that's important to you." It's been a profound exercise. Some of them create a map that doesn't even contain contiguous places, because their sense of the neighborhood is actually three or four geographically separate places in the city. But what I've seen happen is that, especially if there are several people who live in the same neighborhood, the map brings out what people value, what they notice, what they're aware of. They may notice this particular arterial, or that particular wall. Or perhaps this particular tree becomes a landmark for them. Going back to some earlier comments about consensus, we need to value those different views. If you can get all those people in a room together and look at their maps, you can see what it is that stands out to people. And you'll begin to get a better idea of what that community actually is, or what that area actually is—because it is the amalgam of all those perceptions.

Hardesty: Often when we get groups together to talk about what we're going to do in a watershed, we start by asking each person to describe what the watershed would look like if their dreams were fulfilled. How's it going to look? How's it going to sound and smell? How's it going to function? For example, I'm involved in the anti-grazing conflict right now. I hear people say, "We have to get the cows out of there." But when they focus on what the watershed is going to look like, the cows become irrelevant. They may find what they want is a woody overstory; they want lots of vegetation; they want healthy populations of fish and other organisms. And then we start talking about what it's going to take to get it from where it is to where people want it to be—because they generally find what they want is not all that different from what others in the watershed want. Then we can talk about the tools that would get them there. This defuses the conflict over how we're going to get to where we're going to be. Instead it focuses everybody on where we're going to be, by having them actually picture it in their minds and describe that picture.

Baril: Just remember, we spent the last hundred years picking up a lot of expensive skills about how to settle the wilderness, and we ran into the Pacific Ocean. Now we can turn back and spend the next hundred years learning peacemaking skills, as if we are going to live and die together. So I hope we see you at a lot of dances and potlucks.

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PUGET SOUND

RESEARCH '95

SESSION 4C

URBAN STORMWATER ISSUES

Session Chair:

Nancy Hansen

City of Bellevue Storm and Surface Water Utility

SKINNY STREETS AND ONE-SIDED SIDEWALKS: A TECHNICAL AND POLICY STRATEGY FOR NOT PAVING PARADISE

Cedar Wells[1]

INTRODUCTION

As part of our development pattern in the Northwest, we replace natural land covers with impervious surfaces such as buildings, streets, and parking lots. These impervious surfaces block stormwater from soaking into the ground and recharging groundwater, and contribute to increased surface flows, flooding and erosion, degradation of fisheries habitat, and permanent alteration of naturally occurring hydrology and soil structure. Current development and stormwater management practices aim to deal with consequences but fail to directly address the source of the problem—impervious surfaces.

The City of Olympia's Water Resources Program is conducting an Impervious Surface Reduction Study (ISRS) with the assistance of community representatives and neighboring jurisdictions. The study is funded by the Washington Department of Ecology through the Centennial Clean Water Fund and by Olympia residents through their storm and surface water utility.

STUDY APPROACH

From the beginning of the study, a variety of research questions related to impervious surfaces have been identified. Local and nationwide interest in the study has brought to light several water quality and quantity issues that could benefit from more research, including correlation of hydrologic and stream impacts to percent impervious surface land coverage, costs and benefits of various strategies as compared to other stormwater management tools, and impervious surface tracking systems. Many of the water resources problems associated with impervious surfaces cannot be addressed without considering population growth, development patterns, sustainability, and a variety of public goals. Over the next 20 years, the population of Olympia and surrounding North Thurston County is expected to increase by 66 percent. If that growth occurs, impervious surface coverage is expected to double (Thurston Regional Planning Council, 1993). Consequently, the study focuses on identification of impervious surface reduction strategies for urbanizing areas and is designed to complement current growth management planning[2] and Olympia's Sustainability City Criteria[3]. Growth management planning has presented an opportunity to establish policies and regulations that would decrease impervious surfaces associated with new construction and result in less impervious surface per capita. The study assumes impervious surfaces are a well-identified problem and that reduction is a viable strategy for enhancing infiltration capacity. However, reducing impervious surfaces is only one of many stormwater management alternatives and should be considered on a case-by-case basis for cost and management effectiveness. Local governments are urged to explore reduction strategies that are appropriate for their local community, recognizing that impervious surface reduction is still an experiment in finding real-world solutions.

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[1] City of Olympia, Public Works Department, Water Resources Program, 837 7th Avenue S.E., Olympia, WA 98507-1967

[2] The Washington State Growth Management Act was enacted in 1990 and requires local governments in rapidly growing counties to plan for the projected population. Under the act, local governments are required to develop comprehensive land use plans and bring local regulations into consistency with the comprehensive plan.

[3] Olympia's City Council has pledged to evaluate all city policy decisions based on two sustainable city criteria: 1) meet present needs without jeopardizing future generations; and 2) take into account the environmental, economic, social, and political requirements for their success, and their impact on the natural environment and human activities.

STUDY ELEMENTS

Growth Management: An Opportunity for Early Implementation

Concurrent growth management planning has provided an opportunity for early implementation of the study's initial findings. Olympia is revising street, parking, and development standards to bring them into compliance with the Growth Management Act and Olympia's Comprehensive Land Use Plan. The revisions provide a broad arena for considering impervious surface reduction with community goals such as public safety. Narrower residential streets, alternative surfaces, taller buildings, and other strategies have been incorporated into proposed policies and standards. For example, proposed street standards include requirements for 20- and 25-foot-wide local access streets, compared to the existing standard of 32 feet wide. Close coordination of research and policy development with staff in various city departments has been essential to developing policies that complement several community goals. Internal briefings have proven invaluable in "paving the way" for early implementation.

Involvement and Education

The study is guided by both steering and citizen advisory committees. These committees are composed of neighborhood, development, and business representatives, as well as natural resource managers from both the public and private sectors of the local community. The citizen's advisory committee has played a key role in identifying strategies, incentives and barriers, and recommendations. Other avenues for involvement and education have included a needs assessment; community forums and presentations; distribution of fact sheets, reports, and research summaries; and media coverage. Approximately 50 people have been directly involved in the research and development of the study's recommendations. As of March 1995, approximately 1,500 people received information about the study.

Technical And Policy Analysis

Various technical and policy issues were analyzed to increase understanding about problems with impervious surfaces and the costs, benefits, and incentives associated with certain strategies. Key research tasks have included a policy review, basin and site coverage assessment, parking analysis, and demonstration projects. As a result of the coverage assessment and parking analysis findings, several of the study's recommendations address streets and parking.

Policy review

A policy consultant was hired to summarize Olympia and other local government (Lacey, Tumwater, and Thurston County) policies related to impervious surface reduction strategies. The summary was used to determine which local policies currently encourage impervious surface reduction, and helped identify which policies could be modified to further encourage reduction. The summary has served to highlight current accomplishments and possible changes that could be made through growth management planning.

Basin and site coverage assessment

A basin and site coverage assessment of three basins (Figure 1) overlapping the North Thurston Urban Growth Management Area (North Thurston UGMA) was conducted to identify what types of land use and impervious surfaces provide the greatest potential for reduction. The three basins total 37,000 acres and were selected because recent land use and impervious surface coverage data from Hydrologic Simulation Program - Fortran (HSPF) models was readily available, and because the land use and growth patterns in the basins are similar to the North Thurston UGMA as a whole. The assessment indicated that vehicle-oriented pavement, such as streets, driveways, and parking lots, would constitute most of the impervious

surfaces in these basins at 80 percent buildout[1]. The assessment also indicated that the majority of impervious surfaces at 80 percent buildout would be associated with commercial/industrial and high-density residential land uses in these three basins. At 80 percent of buildout, it was estimated that there would be 6,200 acre-feet of stormwater per year added to the runoff currently managed in the three basins.

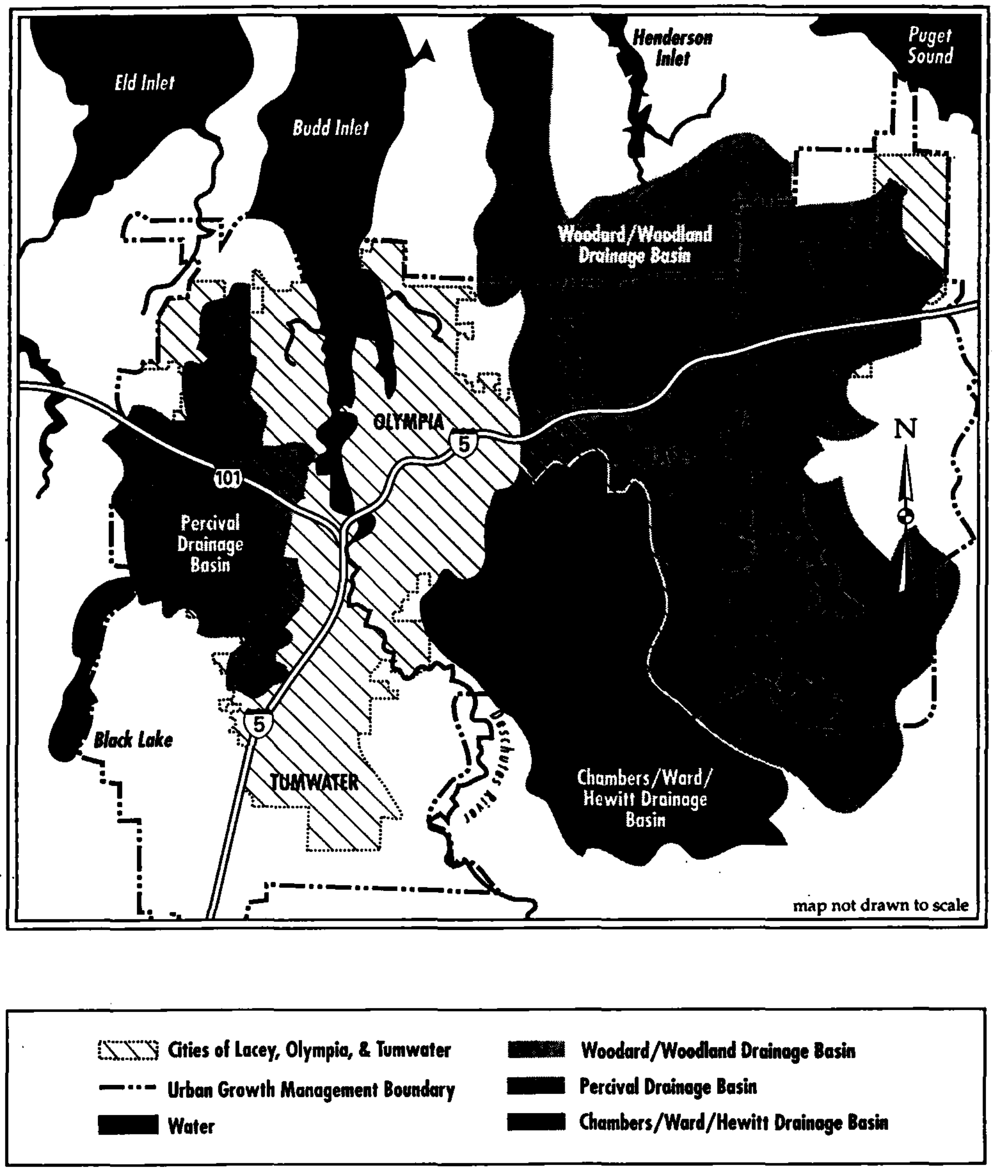

Figure 1. Olympia area basins used in basin and site coverage assessment

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[1] Buildout is typically defined as full development at maximum densities allowed by zoning. However, sites in the Olympia area typically develop at lower levels than allowed by zoning. Using a 80 percent buildout scenario provides a conservative estimate of future impervious surface coverage.

Parking analysis

A parking analysis consisting of a special parking capacity study and cooperative parking survey was conducted to provide information for revising Olympia's parking ordinance. The parking analysis was designed to provide information concerning parking ratios (standards) for each land use, to assess whether proposed median parking ratios would result in less impervious surface than current minimum parking ratios, and to determine whether cooperative parking is a viable strategy for reducing impervious surfaces.

The special parking capacity study consisted of informational interviews, field observations, and a reduction analysis. Interviews of owners and managers of 31 selected sites outside downtown Olympia in the North Thurston UGMA were conducted in August 1994. The interviews asked about peak hours and adequacy of parking capacity. Interview results were then compared to field observations of actual parking stall occupancy. The reduction analysis estimated the amount of impervious surface coverage that could be expected under Olympia's proposed median parking compared to existing minimum parking ratios.

Results of the special parking capacity study indicated a 60 percent to 70 percent vacancy rate among the 31 sites. Even with the high vacancy rates, no owner or manager indicated excess parking was a problem. In fact, the majority of respondents (71 percent) indicated that the amount of available onsite parking was adequate. This discrepancy could be because several respondents indicated that August (summertime) was not the peak season for some businesses. Results also indicated that 38 percent more parking than the existing minimum parking ratios require was built. This finding confirms what planners have known for a long time: that minimum parking ratios do not reflect actual demand or needs, and don't take into account the problems associated with impervious surfaces. This preliminary parking study indicates that Olympia's proposed median parking ratios should result in less impervious surface than would be built under the current minimum parking ratios.

The cooperative parking[1] survey involved interviewing planners from five selected local jurisdictions[2] to assess existing cooperative parking policies and regulations, and to identify barriers and incentives to shared parking[3]. Results indicate that cooperative parking definitions and requirements vary from jurisdiction to jurisdiction, and that this can be a barrier to implementation. Legal agreements are required of cooperative parking participants by all five of the jurisdictions; however, none of the jurisdictions provide model language or agreements. Providing such model language or agreements could encourage more cooperative parking. Shared parking is allowed by the five jurisdictions, even though none actively promotes it or requires it as an alternative to new or larger parking areas. Incentives for cooperative parking include reduced construction, landscaping, and maintenance costs, and the increased ability to complete projects that would otherwise have been denied due to parking deficits. Three jurisdictions offer reductions (5 percent to 25 percent) in required parking if developers agree to share parking.

Demonstration projects

Two demonstration projects are currently scheduled for construction: a sidewalk renovation project at Olympia City Hall and a soil restoration project at Olympia High School. The Olympia City Hall project will incorporate a paver display and information on sources, costs, installation methods, benefits, and limitations of pavers[4]. The goal of the display is to encourage use of pavers in residential settings. The

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[1] Cooperative parking includes various methods to increase the use of available parking areas, including shared, joint, and coordinated parking.

[2] The five local jurisdictions included the cities of Bellevue, Lacey, Olympia, and Tumwater, and Thurston County. All survey participants were planners in local land use and planning departments.

[3] Shared parking is the mutual use of a parking area by land uses with noncompeting hours of operation, such as a theater and office building.

[4] Pavers are concrete grid or modular pavement whose spaces are filled with pervious materials such as sod, sand, or gravel.

soil restoration project will include installation of an infiltration trench along one side of a highly compacted dirt and gravel parking lot, in order to reduce surface runoff to an adjacent soccer field. The 10 by 200 foot trench will contain non-compacted soils with a sub-surface layer of cellular confinement material to reduce compaction of deeper soils. The goal of the Olympia High School restoration project is to assess the effectiveness of cellular confinement technology for parking lots. Results of the two demonstration projects will be available in spring 1996.

RESULTS

Changes In Awareness

The greatest result of the study thus far has been the increased awareness among city staff and citizens. Through committee involvement, presentations and briefings, and dissemination of written materials, city staff are more aware of problems associated with impervious surfaces. At the beginning of the study, impervious surface reduction was not an explicit objective of street, parking, or development policies. Olympia's proposed Unified Development Code currently contains specific policies that will result in reduction.

Many local development and business community members have participated in the production of study materials, and provided insights into incentives and policies they could support. Consequently, the concept of impervious surface reduction is being considered by citizens and staff alike in public processes. Putting the topic "on the table" is a significant first step in achieving actual reduction.

Recommendations for Reduction

Study results have been the basis for 19 recommendations and associated implementation actions. The recommendations are divided into six categories: overall, vehicle-oriented, construction practices and landscaped areas, design and placement of buildings, community involvement and education, and study evaluation. It's expected that at least nine of the recommendations will be wholly or partially incorporated into city policies. Three of the study's recommendations were incorporated into city policy before the study, included only as guidance for other local jurisdictions outside the North Thurston UGMA. If funding is provided and policies are adopted as proposed, Olympia will implement all or part of 81 percent of the study's recommendations not already being implemented. Much of this implementation will begin before the study grant expires. By the year 2020, a 10- to 20-percent reduction in impervious surfaces associated with new construction is expected in Olympia if most of the study's recommendations are implemented.

Such reduction also could be achieved in other communities. Table 1 summarizes some of the key implementation actions local governments could take to reduce impervious surfaces. These actions address the main categories of impervious surfaces: vehicle-oriented pavement, buildings, and compacted soils. Over the next few years, evaluating these actions will be necessary to ascertain their success.

Each community needs to determine which actions are suitable given the specific mix of public goals and community character. Actions appropriate for Olympia may not work for other communities. Local governments interested in achieving cost-effective impervious surface reduction are highly encouraged to involve citizens, businesses, builders and developers in identifying incentives for implementation and real-world solutions.

CONCLUSIONS

Reduction Provides Options

Reducing impervious surfaces associated with new development by 10 percent to 20 percent does not solve the long-term water resource problems with impervious surfaces. However, it does provide some options. Continued population growth and development pressures will result in more urbanized watersheds, and such growth is unsustainable. The list of actions in Table 1 addresses only future development, and does not address existing impervious surfaces. However, reducing impervious surfaces associated with future development can result in the "freeing up" of space that would otherwise be covered with impervious surfaces. In the case of Olympia's three basins used in the basin and site coverage assessment, this amount is estimated to be approximately 600 acres, less than 2 percent of the area. This space could be used for offices, stores, or other development that may have been built on the fringe of the urban core area, allowing for dense development and efficient use of roads and public services. Infill development can result in less impervious surface coverage per capita than would occur with a more sprawling development pattern. The space also could be used for parks or other urban amenities. Reducing impervious surfaces ultimately needs to be linked to land use policies and growth management policies.

Table 1: Selected impervious surface reduction actions for consideration by local governments

- Narrow local access streets to 20 or 25 feet in width. Provide adequate parking and emergency vehicle access. Narrow arterials to federal standards in locations where safety can be maintained.
- Use pavers and other pervious surfaces for low-use areas such as overflow parking, emergency access roads, and residential driveways. Promote residential use of pervious surfaces through displays, fact sheets, and demonstration projects.
- Encourage cooperative parking such as joint, shared, and coordinated parking. Require developers to explore cooperative parking, transportation demand management, and trip reduction options before exceeding parking ratios. Develop parking ratios that reflect parking needs, versus single peak day projections. Allow unlimited distances between shared parking partners through an administrative variance. Review current policies for shared parking to determine if proximity requirements for shared parking partners pose a barrier. Provide model legal agreements.
- Encourage underground or under-the-building parking, and the construction of multi-storied parking structures. Provide public financing and revise development standards to allow additional building height and floors if parking is incorporated into buildings.

Construction Practices and Landscaped Areas

- Limit soil compaction and land clearing associated with new development. Require phased clearing and the retainment of high quality native vegetation and undisturbed areas. Encourage measures such as neighborhood covenants and map and plat conditions that protect existing vegetation and undisturbed areas. Revise government-sponsored neighborhood grant programs to allow funding of native vegetation preservation or enhancement projects.

Design and Placement of Buildings

- Modify development standards and zoning codes to require cluster and infill development that decreases impervious surfaces per capita on a regional basis.

Evaluation

- Monitor impervious surface coverage trends and effectiveness of adopted policies. Track developments that incorporate reduction techniques and evaluate long-term effectiveness. Investigate costs and benefits of impervious surface reduction techniques compared with current stormwater management methods.

Need For Additional Research

This study leaves as many questions unanswered as it has answered. More research is needed to better define costs and incentives, hydrological and water quality relationships to impervious surfaces, and perviousness of lawns and other surfaces. Many of the problems with impervious surfaces are not directly linked to water resources. A cumulative impact assessment would provide an opportunity to consider all the costs and benefits of impervious surface reduction, rather than just those related to water resources. A cumulative impact assessment also could provide a broader review of our current development pattern, and be an appropriate opportunity for the local community to develop a long-term strategy to reduce impervious surfaces.

ACKNOWLEDGMENTS

Thanks to Terra Hegy, the Impervious Surface Reduction Study's Centennial Clean Water Fund grant officer with Washington Department of Ecology. Special thanks to members of the study's Ad Hoc Citizen Advisory Committee (Lisa Palazzi, David Putnam, Priscilla Terry, Glenn Wells, Tom Yates, and past member Dick Blinn). Project staff would also like to acknowledge the time and contributions of City of Lacey, City of Tumwater, and Thurston County staff.

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STORMWATER MITIGATION EFFECTIVENESS

Douglas Beyerlein, P.E., and Joseph Brascher[1]

INTRODUCTION

Land development in the Puget Sound region has changed the flow of the many streams that feed the Sound either directly or indirectly via the larger rivers. These streams perform a dual but conflicting role. The streams are used as a storm sewer collection and transport system for runoff, and they provide habitat for salmonids before their journey to the sea.

Land development provides more and faster runoff through the removal of forest soil and vegetation and their replacement with impervious surfaces (roads, roofs, and parking lots) and with grass vegetation. The runoff storage capacity of the forest vegetation and soil is lost. Mitigation measures are usually required for land development to replace this storage capacity and prevent damage to stream habitat when the forest is removed.

In the Puget Sound region, stormwater mitigation measures are based on the idea of controlling runoff from developed areas so that the magnitude of runoff does not exceed that of the undeveloped condition. Peak flows from developed areas are made smaller by delaying and reducing the rate at which the runoff leaves the developed site. This is done by either detaining or retaining the runoff water on site.

Stormwater detention is accomplished by routing the runoff through a pond, tank, or vault that stores the water and releases it at a reduced rate before it enters a stream or other water body. Retention is keeping the runoff on site and infiltrating the water into the ground.

In much of the Puget Sound region, construction of detention facilities (ponds, tanks, and vaults) is the primary means by which increased runoff into the streams from development is mitigated. This is because the underlying soils have low infiltration rates as a result of the compression of silts and clays into a till layer during periods of prehistoric glacial movement through the Puget Sound basin. Because of the poor percolation of water through till soils, infiltration of runoff is generally limited to sandy, outwash soils.

Stormwater mitigation effectiveness can be measured in terms of the ability to increase development without increasing peak stream flows. Stream habitat can be protected when there is little or no increase in the flood flows that define a stream channel through channel scour and stream bank alteration. These defining flood flows are typically in the range of the two-year to 100-year event. As a result, these are the flood flows upon which we can judge the effectiveness of existing stormwater facilities.

WATERSHEDS STUDIED

The U.S. Environmental Protection Agency's HSPF (Hydrological Simulation Program - Fortran) computer program (Bicknell et al., 1993) was used to model the effectiveness of different proposed mitigation measures at different locations in the Puget Sound region. The objective of the hydrologic modeling was to evaluate the effectiveness of stormwater mitigation requirements for new land development in King and Thurston counties.

The methodology was to use the HSPF model to continuously simulate streamflows for (1) May Creek in King County, (2) an East Sammamish Plateau wetland in King County, and (3) Woodland Creek in Thurston County for a 30- to 40-year period of record using both current and future full buildout land-use conditions. The simulated long-term streamflow record was then used to compute flood frequencies for a range of flows at a variety of locations for each water body listed above.

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May Creek, King County

The May Creek watershed in King County has a drainage area of approximately 15 square miles. The stream drains to Lake Washington and includes a portion of the city of Renton on the south side of the watershed and the new city of Newport Hills on the north side. The watershed's population was 16,000 in 1990, with a majority of the residents living in the western half of the watershed. The eastern half of the watershed is mostly rural and forested. In the center of the watershed is May Valley, through which May Creek flows. May Valley is an agricultural valley; much of the valley is in pasture supporting non-commercial farms. King County has designated the eastern portion of the watershed to be outside of the urban growth management area for King County.

In the May Creek watershed, development impacts have resulted in increased flooding. Flooding problems have been observed on May Creek tributaries, along the shorelines of the lakes (Boren and Kathleen) in the watershed, and in the main stem of May Creek in May Valley. For our study, stormwater mitigation of future land development impacts was modeled using the proposed King County drainage standard: KCRTS. KCRTS (King County Runoff Time Series) is based on HSPF continuous simulation modeling. It is expected to replace the SCS-based methodology (SBUH, TR-20, etc.) used in King County for the design and sizing of stormwater detention ponds. The new KCRTS methodology has been demonstrated by King County staff to provide better mitigation than the SCS-based methods currently in use (Jackson, 1994). We wanted to investigate how well it will solve the future flooding problems of the May Creek watershed.

Future full buildout land-use conditions for the May Creek watershed were provided by King County and represented in our HSPF model of the watershed by increasing the impervious area and converting forest land cover to grass, where appropriate. Mitigation was incorporated into the future conditions by adding detention facilities to the model for those new developed areas that will be required to have detention in the future. Future conditions were modeled with and without mitigation to evaluate the effectiveness of the proposed mitigation.

The results of the proposed mitigation for the May Creek watershed are shown in Table 1 and Figure 1 (Beyerlein, 1993). Mitigation is effective on the tributary streams that are affected by urban development, such as Honey Creek, where the increase in the two-year peak flow from current to future mitigated conditions is only 10 percent, compared to a 29 percent increase for no mitigation.

Mitigation is not as effective for the rural portions of May Creek where the major future land-use change will be from forest vegetation to grass as a result of land clearing activities. No mitigation is required for these areas. This lack of mitigation is reflected in the increase in peak flood flows. For example, the East Fork of May Creek will see a 64 percent increase in the future two-year peak flow without mitigation; this is only reduced to 60 percent with mitigation. Other rural tributaries (North Fork of May Creek and Cabbage Creek) are similarly affected.

The main stem of May Creek from May Valley to Lake Washington shows that mitigation is only partially effective in reducing peak flows. In May Valley the future two-year flood increases 18 percent without mitigation, 14 percent with mitigation. The 100-year flood in the valley shows even less mitigation influence. The future 100-year flood increases 22 percent without mitigation, 20 percent with. Downstream at the mouth the future 100-year flood increases 28 percent without mitigation and 27 percent with mitigation.

The lack of effective stormwater mitigation on the main stem of May Creek is mainly due to two factors. (1) The upstream rural areas (East Fork, North Fork, and Cabbage Creek) will have little or no mitigation required; thus, they will add large additional flows to the main stem in May Valley. And (2) May Valley is like a bathtub that slowly fills before draining out at its downstream end. As a result, the timing of the tributary flood flows into the valley is less important than the total volume of water running into the valley. The valley takes 12 to 18 hours to reach peak depth (and flow), and thus, the delay of tributary runoff by a few hours in a detention pond does little to reduce valley flooding. Detention ponds

reduce peak runoff rates from developed areas, but they do not reduce the increased runoff volumes produced by the increased impervious area and conversion from forest to grass.

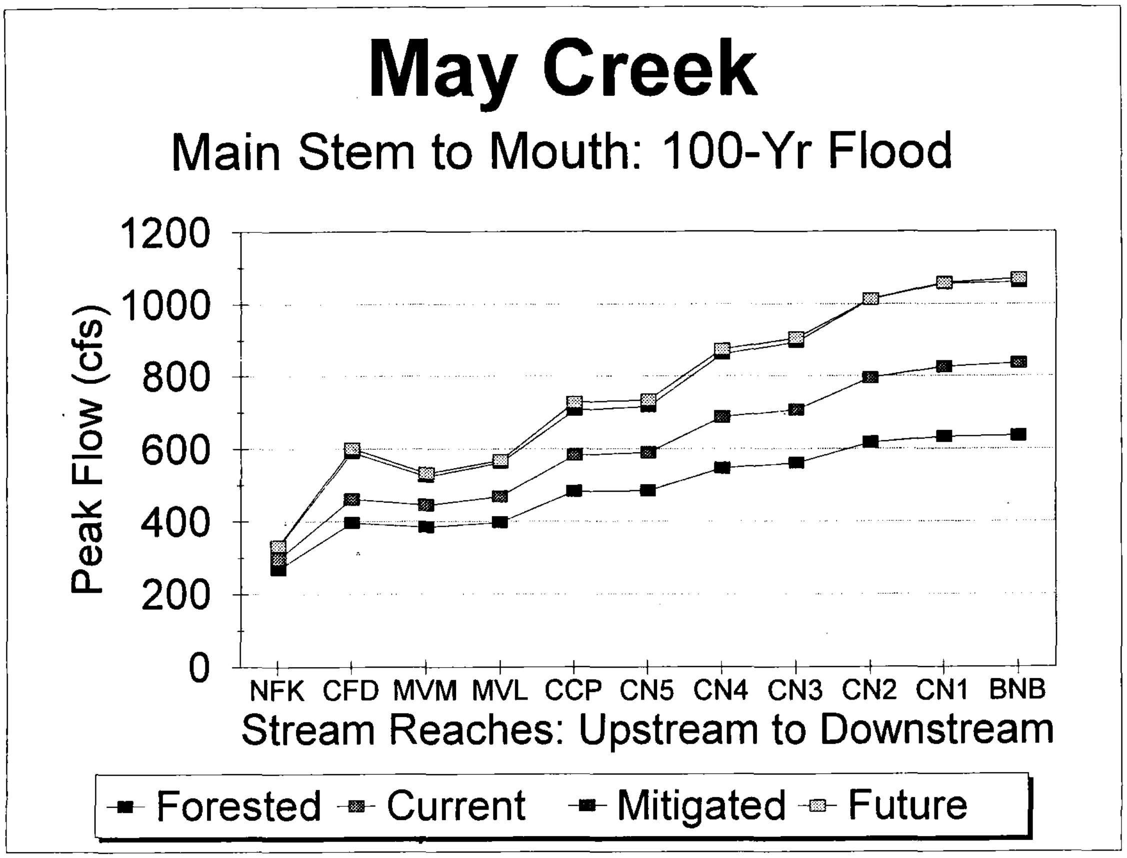

Figure 1.

East Sammamish Plateau Wetland, King County

A privately owned peat wetland on the East Sammamish Plateau in rural King County has been affected by suburban development. The open water wetland is approximately 10 acres in size and is surrounded by a drainage area some 10 times its size. Half of the surrounding drainage area is developed suburban land; half is still covered by forest.

Detention ponds were built to current King County standards for the suburban portions of the watershed. Yet the owners of the wetland have observed increased flooding of the wetland and alteration of the wetland's seasonal water fluctuations or hydroperiod. The current King County mitigation standards are based on SCS (Soil Conservation Service) curve number methodology used in the SBUH (Santa Barbara Urban Hydrograph) program.

An HSPF model was constructed for the wetland and surrounding drainage area. The model allowed us to evaluate the effectiveness of the existing mitigation facilities on the adjacent wetland compared to no mitigation and natural, predeveloped land-use conditions.

As shown in Figure 2, existing mitigation facilities do little to reduce the impacts of the additional runoff from adjacent suburban land. As with the problems observed in May Valley, this situation is largely due to the fact that because of the wetland's long water storage period (weeks), runoff volume is more important than runoff peak rates. The existing mitigation facilities control runoff peak rates; they do

Table 1. May Creek increase in flood size from current conditions

Subcatchment	Name	2-year flood forested (cfs)	2-year flood current (cfs)	2-year flood future (%)	2-year flood mitigated (%)	10-year flood forested (cfs)	10-year flood current (cfs)	10-year flood future (%)	10-year flood mitigated (%)	100-year flood forested (cfs)	100-year flood current (cfs)	100-year flood future (%)	100-year flood mitigated (%)
HIGHLANDS													
EFK	East Fork	35	42	64%	60%	57	68	49%	46%	89	102	41%	38%
NFK	North Fork	105	123	43%	37%	175	199	25%	22%	268	296	12%	11%
CAC	Cabbage Creek	43	46	78%	70%	77	81	63%	53%	126	133	55%	45%
COU	Country Creek	24	26	112%	35%	42	46	85%	37%	70	77	65%	40%
LMC	Long Marsh Creek	40	42	19%	2%	71	75	13%	4%	118	125	11%	4%
WT4	Wetland 4	7	9	67%	11%	12	15	73%	33%	20	25	68%	52%
LBU	Lake Boren Upper	16	23	22%	13%	28	43	26%	16%	47	72	40%	28%
LBL	Lake Boren Lower	21	36	42%	17%	36	62	39%	23%	60	103	40%	33%
EAST RENTON PLATEAU													
LKA	Lake Kathleen	5	5	20%	20%	6	8	38%	38%	8	13	54%	54%
LKC	Lake Kathleen Creek	11	17	18%	12%	17	26	19%	15%	24	36	33%	31%
PSC	Greenes Creek	10	26	58%	23%	18	42	57%	21%	31	68	56%	21%
RHC	Renton Highlands Creek	17	33	30%	18%	27	51	33%	22%	42	76	37%	26%
HCU	Honey Creek Upper	7	19	79%	16%	13	30	77%	13%	21	45	80%	16%
HCM	Honey Creek Middle	13	43	16%	7%	23	52	-2%	0%	37	60	-13%	-5%
HCL	Honey Creek Lower	20	63	29%	10%	36	85	19%	6%	59	109	13%	4%
MAY VALLEY													
CFD	Coalfield	151	170	19%	14%	250	285	26%	22%	396	461	30%	28%
MVM	May Valley Middle	143	164	16%	12%	242	276	20%	17%	385	445	20%	18%
MVL	May Valley Lower	141	165	18%	14%	245	285	22%	19%	397	468	22%	20%
CCP	Coal Creek Parkway	173	208	22%	17%	299	357	23%	20%	482	582	25%	21%
LOWER BASIN													
CN5	Canyon 5	175	210	23%	17%	301	361	23%	20%	485	589	25%	22%
CN4	Canyon 4	195	245	26%	16%	337	420	26%	21%	546	687	27%	25%
NHC	Newport Hills Creek	6	12	75%	17%	10	20	70%	10%	16	31	74%	10%
CN3	Canyon 3	200	255	29%	16%	346	435	27%	21%	560	707	28%	26%
GYP	Gypsy Creek	6	16	56%	13%	10	25	56%	16%	16	38	58%	16%
CN2	Canyon 2	217	316	31%	15%	377	521	26%	18%	617	794	28%	27%
CN1	Canyon 1	223	336	33%	16%	387	548	28%	19%	633	825	28%	28%
BNB	Lower May Creek	223	341	33%	15%	389	556	27%	17%	636	835	28%	27%

nothing to control total runoff volume. Consequentially, additional runoff is only slightly delayed in reaching the wetland. But with or without the delay caused by the detention ponds, the wetland is still flooded to an unnatural depth, and it is flooded more often because of the extra runoff from the adjacent suburban area.

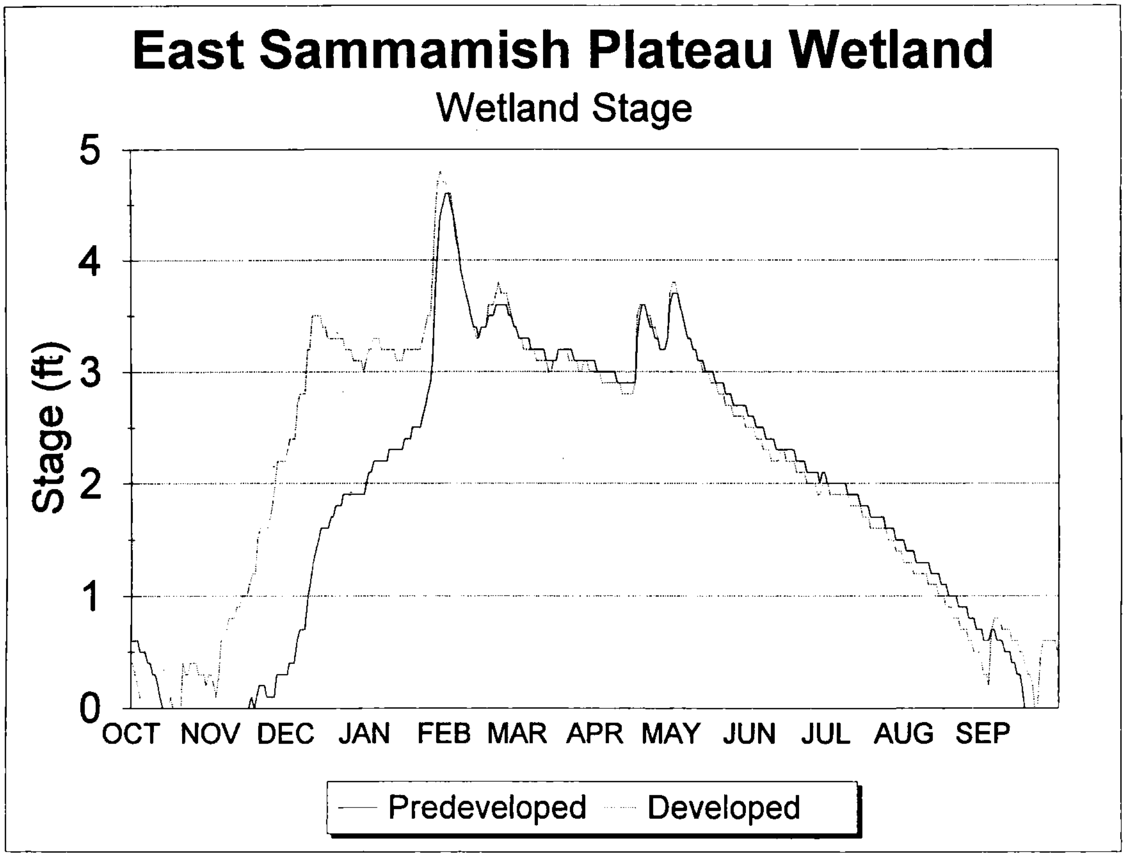

Figure 2.

The significance of the additional runoff flooding the wetland and altering its hydroperiod can be judged using criteria developed by Dr. Rich Horner as part of the Puget Sound Wetlands and Stormwater Management Research Program (Horner, 1994). The criteria provide eight hydroperiod guidelines of wetland water depth and duration of flooding, which can be examined using the continuous water depth data generated by the HSPF model of the wetland.

A comparison of the wetland's simulated water depth with and without the neighboring suburban development showed that seven of the eight guideline hydroperiod alterations were exceeded because of additional runoff volume from the development. The seven guidelines that are exceeded are:

(1) limit annual maximum depth increase to 30 cm (1.0 ft);

(2) limit average monthly water level fluctuation (WLF) increase to 5 cm (0.2 ft);

(3) limit stage excursions (number of occurrences) to a maximum of 8 cm (0.3 ft) for a duration of 24 hours in any 30-day period between 1 February and 31 May (the growing season);

(4) limit maximum depth increase to 30 cm (1.0 ft) during the period of 1 June through 30 September;

(5) limit stage excursions to a maximum of 15 cm (0.5 ft) for a duration of 72 hours in any 30-day period between 1 June and 30 September;

(6) limit water depth increase of any amount to no more than once per year (specific to peat wetlands); and

(7) limit stage excursions to a maximum of 15 cm (0.5 ft) for a duration of 24 hours in any 30-day period (specific to peat wetlands).

The only guideline that was not exceeded is the limitation of the increase or decrease in the dry period to two weeks.

The existing stormwater mitigation is ineffective in protecting this wetland from the impacts of development in this watershed.

Woodland Creek, Thurston County

The Woodland Creek watershed is located in northern Thurston County and includes a portion of the City of Lacey. The watershed is 29 square miles in area and drains to Henderson Inlet near the south end of Puget Sound. There are three major lakes in the southern portion of the watershed with most of the development occurring along the I-5 corridor, which cuts across the middle of the watershed. The southern two-thirds of the watershed contain outwash soils, which are very sandy with high infiltration rates. The northern third of the watershed is mostly covered by till soils (low infiltration rates). Much of the northern portion of the watershed is also outside of the Growth Management Area for Thurston County.

In the Woodland Creek watershed development impacts have resulted in increased flooding of Woodland Creek and its tributaries. For the purposes of our study, stormwater mitigation of future land development impacts was modeled using the 1994 Thurston County drainage standards. These standards require the infiltration of excess runoff from new development wherever possible. Detention ponds are required for new development on till soils. In addition to modeling Thurston County's drainage requirements for new development, we also evaluated possible regional detention projects in the watershed. All of these projects are located on tributaries to Woodland Creek except for a proposed outlet control structure on Long Lake. This study was funded by the U.S. Geological Survey and Thurston County (Beyerlein and Brascher, 1994).

Future full buildout land-use conditions for the Woodland Creek watershed were provided by Thurston County and represented in our HSPF model of the watershed by increasing the impervious area and converting forest land cover to grass, where appropriate. Mitigation was incorporated into the future conditions by adding detention facilities to the model for those new developed areas that will be required to have detention in the future. Future conditions were modeled with and without mitigation to evaluate the effectiveness of the proposed mitigation. Regional facilities were added where appropriate in an attempt to reduce future flood flows to no increase over current flood flows. This situation is labeled Service Level 1. Further reduction in future flood flows was accomplished by doubling the drainage manual's detention requirements (Service Level 2A) and by adding cluster development to those areas where future conversion to suburban land use will remove forest vegetation from the watershed (Service Level 2B).

The results of the proposed mitigation for the Woodland Creek watershed are shown in Table 2 and Figure 3. Mitigation is effective where infiltration is required. The increase in the 100-year Woodland Creek peak flow at Martin Way (in the I-5 corridor) from current to future mitigated conditions is only 10 percent, compared to a 165 percent increase for no mitigation. However, downstream tributaries that drain till soils show the mitigation requirements to be less effective in these areas. For example, Eagle Creek 100-year peak flow increases from 63 cfs for current conditions to 187 cfs for future mitigated conditions (an increase of 197 percent) and 381 cfs for future unmitigated conditions (505 percent increase). Eagle Creek peak flows are partially mitigated by the drainage manual requirements, but are still almost twice that of current land condition peak flows.

Table 2. Woodland Creek 100-year flood flows: all scenarios

Scenario: Subbasin Number	Subbasin Name	Forested (cfs)	Current (cfs)	Future w/o Manual (cfs)	Future w/Manual (cfs)	Service Level 1 Future w/projects (cfs)	Service Level 2A Future w/double manual (cfs)	Service Level 2B Future Cluster (cfs)
50	Pattison Lake outlet	30	41	46	44	44	44	43
60	Long Lake outlet	27	43	56	49	38	37	36
8	Subbasin 8 trib	0	23	23	24	24	24	24
80	Lake Lois outlet	16	36	60	40	40	32	32
9	Lacey, Goose Pond Area	0	0	479	0	0	0	0
100	creek at Martin Way	39	69	183	76	71	71	70
13	Lower College Creek	12	52	138	107	27	22	22
14	Middle College Creek	15	61	136	95	25	23	23
15	Upper College Creek	4	30	80	43	15	15	15
17	Thompson Place trib	23	87	716	128	128	91	91
180	creek at Draham Rd	66	187	854	283	213	180	180
21	Eagle Creek	44	63	381	187	95	84	80
22	Palm Creek	9	17	63	32	6	6	6
23	Fox Creek	35	47	110	92	17	17	17
240	creek at Pleasant Glade	139	306	1430	583	317	264	260
25	Jorgenson Creek	19	27	98	54	12	12	12
270	Mouth	227	455	1702	727	471	426	393

To return future peak flows to current levels (the goal of Service Level 1) we also investigated the addition of individual regional detention projects. The majority of these projects are located on the tributaries in the northern half of the watershed (north of the I-5 corridor). In general, these proposed projects have sufficient storage volume to reduce future peak flows to near or below current peak flows. For example, the Eagle Creek future 100-year peak flow is reduced from 187 cfs to 95 cfs with the addition of a regional stormwater detention project on the creek. The current 100-year peak flow is 63 cfs.

For some Woodland tributaries the regional projects reduced the future 100-year peak flow to below the predevelopment forested 100-year flow. Examples of this situation are Palm Creek (forested: 9 cfs; project: 6 cfs), Fox Creek (forested: 35 cfs; project: 17 cfs), and Jorgenson Creek (forested: 19 cfs; project: 12 cfs). Yet even with these substantial reductions in tributary peak flows the main stem of Woodland Creek still had future 100-year peak flows greater than current conditions (471 cfs at mouth versus 455 cfs for current conditions) at Service Level 1.

Additional mitigation was required to further reduce Woodland Creek future peak flows. The drainage manual detention pond requirements were doubled (Service Level 2A) to evaluate what impact that will have in further reduction of peak flows beyond the Service Level 1 requirements. Because of the previously discussed impact of the regional projects on the tributaries, the doubling of the drainage manual standards made a difference only in areas with till soils that drain directly to Woodland Creek. This can be observed in the reduction in main stem future 100-year peak flow at the mouth, which decreases from 471 cfs (Service Level 1) to 426 cfs (Service Level 2A). Current condition 100-year peak flow is 455 cfs.

The last mitigation measure to be investigated for Woodland Creek was the introduction of cluster development in forested till soil portions of the watershed (Service Level 2B) in addition to Service Level 2A regulations and projects. Cluster development was represented by increasing the forested land outside the urban growth management area from 20 percent to 70 percent of the current forest cover. Development was concentrated on the remaining 30 percent of the available land. As is true for Service Level 2A, the protection of forest vegetation made a difference only in areas with till soils that drain directly to Woodland Creek because of the impact of the Service Level 1 projects on reducing tributary streamflow. This is observed at the mouth of Woodland Creek, where the Service Level 2A 100-year peak flow is 426 cfs and the Service Level 2B 100-year peak flow is 393 cfs—an 8 percent reduction. Without the Service Level 1 regional detention projects, the cluster development would have a greater impact on reducing flood flows in the Woodland Creek watershed.

SUMMARY

Standard stormwater mitigation measures are not completely effective in protecting water bodies and stream resources. This is because (1) mitigation is not required for the land conversion from forest vegetation to grass, and (2) peak flow mitigation does not reduce total runoff to water bodies (streams, lakes, and wetlands) where the water body's storage time is greater than the detention pond's storage time required by mitigation.

Mitigation can be successful where (1) infiltration is required, and (2) detaining and reducing peak flow runoff delays the runoff sufficiently to prevent it from adding to downstream problems. Detention works best where runoff drains directly to a flashy stream. In this situation delaying the runoff by a few hours will prevent it from adding to the stream's existing peak flow.

If full mitigation of future land-use impacts is a goal to save existing water resources of the Puget Sound basin, then more strict development controls will be required. Specifically, mitigation should be required for land conversion from forest to grass. Additional mitigation for impacts to streams, lakes, and wetlands that have long peak flow and/or depth durations should be investigated and alternative solutions found for discharge from standard stormwater detention facilities.

ACKNOWLEDGMENTS

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WATER QUALITY PROTECTION—YOUR HIGHWAY TAX DOLLARS AT WORK

Shari Schaftlein[1]

INTRODUCTION

This paper describes the progress in developing a stormwater management program at the Washington Department of Transportation (WSDOT). Topics highlighted include the inventory and field screening of outfalls in Puget Sound, the effort to prioritize outfalls for retrofitting, implementation of the Highway Runoff Manual, development of the National Pollution Discharge Elimination System (NPDES) municipal stormwater application, and WSDOT-funded water quality research.

The key regulatory framework under which the program is developing includes Chapter 173-270 WAC (Puget Sound Highway Runoff Rule) and NPDES municipal stormwater regulations under the Federal Clean Water Act. The Runoff Rule states that WSDOT shall complete all practicable Best Management Practice (BMP) projects for stormwater treatment for highways with an Average Daily Traffic (ADT) of 50,000 or greater by December 31, 2005, and for other highways by December 31, 2015. Per the NPDES requirements operators of a storm sewer system serving areas with a population greater than 100,000 are required to get a permit for stormwater discharges. WSDOT highways located in the following areas are subject to permit requirements: unincorporated Snohomish, King, and Pierce Counties and the cities of Seattle and Tacoma. The permit application process requires that:

1) a comprehensive stormwater management program be developed;
2) an inventory be conducted to identify storm water sources and impacts;
3) a discharge characterization and monitoring program be developed; and
4) illicit connections be identified and a prevention plan be developed.

The proposed stormwater management program is submitted as part of the permit application. Each program element consists of a task description, implementation schedule, evaluation, and budget. Program elements include: Illicit Connections, Construction Site Runoff, New Construction and Retrofit BMPs, Maintenance, Sampling, and Public Education.

OUTFALL INVENTORY

Methodology

Since July 1993 field crews have been conducting a stormwater drainage inventory on the state highways within the Puget Sound Basin. Unlimited access highways within incorporated communities were not surveyed because these roads are maintained by the local road department. The inventory consists of: outfalls (those sites where highway runoff is collected and discharged to surface water, groundwater, and municipal storm sewers); existing stormwater structures providing quantity and quality control (BMPs); and offsite potentially illicit connections to the WSDOT drainage system. Information on each drainage structure was collected during a visual inspection in the field and recorded on a field data sheet. Characteristics recorded for the drainage structures include:

1) Outfalls—inventoried as belonging to one of the following four categories:

- Culverts 12 inches or larger—shape, size, material, condition, blockage. Culverts under this size were also inventoried if they drain directly into surface water (e.g. from a bridge surface).

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- Open channels discharging to surface water or leaving WSDOT right-of-way—lining (vegetation, soil or an impermeable material such as asphalt or concrete), dimensions, amount of vegetation, and degree of obstruction.
- Interconnections between municipal storm drain systems and the WSDOT drainage system.
- Dry wells. These were inventoried as both outfalls and water quantity BMPs, as they remove runoff from the road surface but also discharge it, untreated, to aquifers.

2) Existing Best Management Practices (BMPs). Water quality and quantity BMPs were categorized as one of the following types: infiltration trenches, dry ponds, dry wells, wet vaults, wet ponds, oil/water separators, biofiltration swales, or spill control structures. Ecology ditches and catch basin filters were inventoried as experimental BMPs. Erosion control BMPs associated with permanent BMPs were also noted—hay bales, rock check dams, silt fences, etc.

3) Connections to WSDOT right-of-way from off site. These are pipes or open channels that are connected or convey stormwater to the WSDOT drainage system from off the right-of-way. The Utility Permit database was reviewed to determine whether approval to make the connection had been applied for and recorded. In addition engineering and maintenance personnel were contacted to locate areas where off-site drainage was permitted. Non-permitted or unknown connections were documented as illicit.

The inventory was accomplished by: reviewing construction plans; consulting both regional WSDOT personnel and local public works departments; and locating structures in the field. The screening assessment for potential water pollution problems was made from observations and if necessary sampling. Global Positioning System (GPS) equipment is being used to obtain accurate locations for the outfalls. Data sheets are entered on a computer database using Filemaker™ software. Key attributes for each outfall are being loaded into a stormwater outfall layer in a Geographic Information System (GIS), which is an ArcInfo™ format.

Because of time constraints, a faster field screening protocol known as "windshield survey" was established for certain low-ADT highways. Using this protocol, the field crews were able to characterize long sections of homogeneous rural highways. Field notes were taken on general drainage characteristics, and outfalls that discharged directly to surface water were inventoried.

Survey Results

There are approximately 1,675 miles of state highways in the Puget Sound Basin, all of which lie within the boundaries of WSDOT's Northwest and Olympic Regions. As of January 1995 the inventory work has been completed on 955 miles, and these break down by county as follows (total miles/miles inventoried): Clallam (113/0); Island (51/8); Jefferson (88/0); King (332/298); Kitsap (89/62); Mason (119/12); Pierce (269/259); Skagit (167/100); Snohomish (216/88); Thurston (56/38); Whatcom (175/90). Highways in Kitsap, Mason, Pierce, Thurston, and southern King counties with an ADT below a threshold of 10,000 were inventoried using the windshield survey protocol. In Skagit and Whatcom counties the ADT threshold was 20,000.

There are three water quality management areas in the Puget Sound Basin scheduled to be permitted in June. The permit areas and inventory progress are as follows:

1) Cedar-Green: All but 30 rural miles of approximately 200 miles of state highways within the permitted jurisdictions have been inventoried.

2) Island-Snohomish: There are 218 miles of state highways in the permitted jurisdictions, of which 71 miles have been completed. The remaining 147 miles have an ADT of under 20,000 and will be inventoried by windshield survey.

3) South Puget Sound: There are 274 miles of state highways in the permitted jurisdictions, of which 264 miles have been inventoried.

Puget Sound Basin Outfall Inventory Results

- Outfalls: There are 2,198 outfalls characterized and inventoried, of which 1,283 are culverts ranging in diameter from 4 to 84 inches, 704 are open channels, 186 are pipes to other jurisdictions' storm drainage systems, and 25 are dry wells. Of the 1,359 outfalls that drain directly to surface water, 90 receive treatment in a BMP and 1,269 do not.
- BMPs: There were 203 BMPs characterized, consisting of 75 wet ponds, 46 dry ponds, 25 dry wells, 30 oil/water separators, 12 wet vaults, nine biofiltration swales, four infiltration trenches, one spill containment structure, and one ecology ditch. In several areas there were natural features, such as a grass-lined channels, that were offering some water quality benefits; these were not counted as BMPs, but treatment benefits were noted on data sheets.
- Connections: There were 66 connections identified, of which 42 were dry and 24 were flowing. Twenty of these connections discharge directly to surface water without any treatment and 10 are treated by BMPs before being discharged.

By July, inventory work including GPS and data entry work will be completed on the all remaining highways within King, Pierce, Snohomish and Kitsap County. The highways remaining in Thurston and Mason counties, and those along Hood Canal, may be inventoried if additional resources become available.

FIELD SCREENING AND WATER QUALITY SAMPLING RESULTS

A protocol based on federal regulations was established to sample the outfalls for possible illicit connections (WSDOT, 1993). Sampling was conducted at outfalls where illicit connections or discharges were suspected, the main cause for suspicion being discharge after a period of dry weather. Each flowing site was sampled twice within a 24-hour period and was analyzed according to EPA-approved methods, for the following Physical and Chemical parameters: color, odor, scum, floatables, turbidity, temperature, pH, chlorine, copper, phenols, and detergents.

Because of the extension of the field screening process into fall and winter wet weather, flows were observed at 380 outfalls and 24 illicit connections. Of these flows, 76 outfalls and 11 illicit connections were sampled. Elevated levels were detected at 19 outfalls and seven illicit connections. The rest of the flows were determined to be from natural sources, such as springs or a groundwater table near the surface, with no visible signs of contamination, so sampling was not conducted. Physical observations and chemical analyses are as follows (note: elevated levels are concentrations at 0.2 mg/l. or greater):

- Color. All samples appeared close to transparent in color.
- Odor. Odors were detected at six sampling sites. These were either musty and rancid, strong petroleum, muddy or sewage.
- Scum. Scum was recorded at seven sampling sites, one of which was an illicit connection from a commercial area.
- Floatables. Eight sampling sites had a petroleum sheen and one had algae associated with sewage. The source was believed to be a faulty septic system.
- Turbidity. The majority of the samples had low turbidity ratings; however, elevated levels of turbidity were recorded at nine sites.
- pH. The normal pH results ranged from 6.5 to 8.0. There were 10 outfalls and three illicit connections where the pH levels were recorded outside this range.
- Chlorine. Elevated levels of chlorine, from 0.3 to 3.0 mg/l, were detected at three outfalls and one illicit connection from a commercial area.
- Copper. Elevated levels of copper, ranging from 0.25 to 2.0 mg/l, were detected at six outfalls and three illicit connections. Elevated levels from three of the outfalls and two of the illicit connections

were located in King County. These may be from high concentrations of copper that occur naturally in the groundwater in many parts of the county. Another possible source is leaching from copper in pipes.

- Phenols. Elevated levels of phenols were recorded, at 0.5 mg/l, at two outfalls and one illicit connection.
- Detergents. Elevated levels of detergents were detected, from 0.2 to 0.9 mg/l, at 12 outfalls and five illicit connections. At one of the illicit connections detergents were also visible in the flow. The highest level (0.9 mg/l) was recorded at an illicit connection from a commercial area.

It was concluded that the field sampling process was not an effective method for discovering illicit connections. The most effective method is simple visual identification of connections to the WSDOT drainage system, and tracing these back to their sources off right-of-way. No illicit connections were discovered by sampling alone. Sampling does not help in discovering illicit connections unless these are flowing at the time of sampling. Instead it may be more useful in providing additional confirmation of an already suspect site.

ILLICIT CONNECTIONS

Illicit connections are unauthorized drainage structures that potentially convey non-stormwater discharges to, or through, the WSDOT drainage system from off-right-of-way locations. There are 66 connections so far that appear to be suspect and could potentially lead to water quality and quantity problems. Of these connections, three were open channels, which were considered to be illicit connections as a result of visual evidence of the nature of the discharges in the channels, e.g., heavy sediment loading from dredging or construction upstream. The other 59 connections were from culverts, ranging in diameter from 1 to 48 inches.

Flows were observed at 24 of the illicit connections, and 11 of these were sampled. Elevated levels of either turbidity, pH, chlorine, copper, phenols, or detergents were found in the flows from seven illicit connections. All of these connections were located on highways in commercial/residential areas. The flows from the other 13 connections were considered to be from natural sources, with no visible evidence of contamination, and therefore were not sampled. The illicit connections were primarily located in urbanized areas. Additional investigation and/or periodic monitoring of these sites is recommended. For confirmed illicit connections it is recommended that property owners be notified and that either the connection be removed or the flow be diverted to prevent it from entering the WSDOT drainage system.

The database of illicit connections produced by this inventory does not represent a comprehensive survey for the Puget Sound Basin. Only those connections in close proximity to outfalls were observed. A complete inventory would entail walking the entire length of the state highway. Since this is not practical it is recommended that when maintenance crews observe contamination or flooding problems that the area tributary to the problem site be surveyed. Given the minimal complaints received in the past and the low number of illicit discharges discovered to date it is concluded that contaminated illicit discharges are a minor problem.

RETROFIT PROGRAM

One of the primary goals of the Outfall Inventory and Field Screening project was to determine which areas of the drainage system have the greatest impact on receiving water bodies. Beginning with the 1995-97 biennium, WSDOT is developing a new project category for constructing BMPs for existing highways where a need for stormwater management improvement has been identified. The stormwater retrofit category will provide funds for projects that will construct BMPs at locations where no future improvements to the highway are anticipated. It has been estimated that the capitol cost for stormwater retrofit projects in Puget Sound will require upwards of $200 million over the course of 20 years (Entranco, 1992). An actual funding level will be determined on a biennial basis by the Legislature and governor. The WSDOT Agency Funding Request for the next biennium is projected at $4.6 million.

Prioritization Scheme

In order to compare outfall impacts and rank sites for retrofit funding, a prioritization scheme was developed (WSDOT, 1993; Entranco, 1992). The equation and factors used in making prioritization and BMP planning decisions were:

$$(A + B) + (C \times D) + (E + F) = \text{Rating Score}$$

A = water body type (ground water, small stream, small lake, sensitive wetland, large lake, river, wetlands and tidelands) and size of the receiving water body. A small stream is assigned a higher impact value than a large stream.

B = beneficial uses of the water body (in descending priority: drinking, public health, fisheries, aesthetics, and flood protection).

C = pollutant loading, which is in direct proportion to ADT.

D = percentage contribution of highway runoff to the watershed.

E = cost/pollution benefit, which weighs the overall cost of the BMP retrofit against its benefit to the receiving water body. This factor also incorporates a coefficient to consider the size of the waterbody as a measure of its sensitivity to pollution.

F = values trade-off, which assesses how local environmental and societal factors, such as legal obligations or local watershed action plans, influence the construction or maintenance of the BMP retrofit.

The initial step in the prioritization process was to make a "first cut"of all the outfalls inventoried. The outfalls were divided into high-, medium-, or low-priority categories, based on the best professional judgment of the inventory crews. The outfalls in the high category were further evaluated according to factors A, B, C and D in order to determine the highest priority group for further research.

As a result of the first cut the 2,143 outfalls were divided as follows: 498 were high priority, 593 were medium priority, and 1,107 were low priority. Extensive research and evaluation of all six factors were conducted on the highest priority outfalls from within the high category, in order to rank these sites. Recommended BMP retrofits, were developed for each of these outfalls, or groups of outfalls. A retrofit could include either constructing a new BMP (e.g., a biofiltration swale and wet pond) or modifying an existing structure (e.g., changing an asphalt-lined open channel to a biofiltration swale). The complete prioritization scheme was then applied to these sites to obtain a score and final rank.

Findings

So far, 210 high priority outfalls within the Puget Sound Basin have been researched and prioritized. Of these 169 are located within one of the three NPDES permit areas. The four highest-ranked outfalls scored 72 points out of a maximum of 91, and were grouped together into one BMP retrofit site. This site is located on SR5 in Whatcom County, and is tributary to Lake Samish, a public drinking water supply.

The prioritization of the outfalls is an ongoing process and rankings will change as more are prioritized and conditions such as funding and regulations change. However, from the results of the initial prioritization conducted for the 1995-97 budget process, the highest ranked sites typically:

- are on the highways with the highest ADT, particularly SR5;
- threaten drinking water supplies;
- drain tight-line storm trunk systems, and discharge to headwater streams, contributing to erosion, sedimentation and flooding downstream;

- are dry wells discharging to a sole source aquifer; or
- present a significant risk of hazardous spills entering a water supply.

HIGHWAY RUNOFF MANUAL

The Department of Ecology recently granted a two-year interim approval of the Highway Runoff Manual (HRM). The HRM establishes minimum requirements and provides technical, uniform guidance on how to avoid and reduce impacts to water resources. It contains the comprehensive listing, design standards, maintenance requirements, and other related information on stormwater BMPs. The HRM is a primary tool in planning for highway runoff management because it assists with determination of cost-effectiveness, practicability, and applicability of the various stormwater BMPs available to treat highway runoff. The minimum requirements described in HRM address:

Erosion and Sediment Control
Preservation of the Natural Drainage System
Source Control
Water Quality Treatment
Water Quantity Treatment
Wetland Protection
Downstream Analysis
Sensitive Areas and Basin Plans
Stormwater Site Plan

All new impervious surfaces will be treated to standard. Where existing pavement occurs within a project boundary, a practicality analysis will be done to determine whether stormwater quality treatment will be provided. The analysis will be provided in the Stormwater Site Plan.

WSDOT-FUNDED RESEARCH PROJECTS

Stormwater research has increased significantly. Many of the research projects are being led by Washington State University (WSU); however, WSDOT staff, consultants, and local units of government are also involved in several projects. Project descriptions and the lead research organization are as follows:

- WSU: assessment and application of highway slopes for highway stormwater contaminant removal.
- WSU: development of sedimentation basin design criteria by scale model testing.
- WSU: enhanced stormwater contaminant removal by chemical action. (A low-tech method of applying selected pH-adjusted coagulating chemicals to enhance sediment and contaminant removal efficiencies is being developed.)
- WSU: assessment of groundwater pollution potential resulting from stormwater infiltration BMPs.
- WSU: treatment of non-point runoff using catalytic pavement borders. (The goal is to develop a low-tech, low-maintenance system that destroys hydrocarbons in runoff before they leave the pavement.)
- Consultant: BMP effectiveness monitoring on the ecology ditch. (This experimental BMP is designed to remove pollutants through biofiltration and infiltration. It consist of an 8-inch perforated pipe backfilled with gravel aggregate. The surface of the ditch consists of lime and alder sawdust mixed into the top 2 inches of the gravel aggregate. The surface of the ditch is covered with a 4-foot-wide strip of erosion control blanket and is fertilized and hydroseeded.)
- WSDOT: construction site sampling at SR 18 project. (A King County grading permit condition requires daily sampling for turbidity and settleable solids.)
- WSU: stormwater retrofit cost/benefit estimating project.

- King County study receiving partial WSDOT funding: assessment of relative storm runoff control advantages of alternate roadway shoulder pavements.
- WSU: filter strip/ecology ditch field evaluation.
- WSU: BMP evaluation for handling and treating stormwater in confined situations. (Determines effective BMPs for where limited right of way situations. The most effective BMPs for treating stormwater in urban areas, including ferry dock and terminal areas, have a number of product options which are used mostly based on the claims of the product manufacture.)
- BMP effectiveness monitoring per NPDES municipal permit requirements. (This sampling will involve coordination with all the permitted municipalities.)

ACKNOWLEDGMENTS

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WASHINGTON STATE PESTICIDE MONITORING PROGRAM: SURFACE WATER RESULTS FOR THE PUGET SOUND BASIN

Dale Davis[1]

ABSTRACT

Surface water samples for the Washington State Pesticide Monitoring Program (WSPMP) were collected in 1992-1994 at five sites in the Puget Sound area, and analyzed for 162 pesticides and breakdown products. The collection frequency was three times per year—spring, summer, and fall.

Twenty-four different pesticide compounds have been identified in samples from these five sites. Five pesticides were detected exclusively at the urban sites, six exclusively at the agricultural sites, and 13 at both. The herbicides DCPA (Dacthal) and 2,4-D were the only compounds found at all five sites. The greatest number of pesticides was detected in Bellevue's Mercer Creek (18), equaled only by irrigation return flows in the Yakima Basin sampled by the WSPMP.

Washington State and/or EPA aquatic life criteria are available for only one pesticide (malathion) detected in the Puget Sound area, and the concentration was below the criterion. Three organophosphorus pesticides, diazinon, malathion, and mevinphos (Phosdrin), have been detected at or above National Academy of Sciences recommended maximum concentrations for protection of aquatic life and wildlife. Mevinphos was found in Joe Leary Slough (Padilla Bay) at a concentration above the 96-hour LC_{50} for rainbow trout.

The information gathered so far in this study, although limited, is the only pesticide data available for many water bodies in the state. However, a substantially greater effort will be required to achieve an adequate understanding of the occurrence and significance of pesticide residues in Puget Sound rivers and streams.

INTRODUCTION

As a result of growing concerns about pesticides in state waters, the Toxics Investigations Section of the Washington Department of Ecology developed and implemented the Washington State Pesticide Monitoring Program (WSPMP) in 1992. The program goal is to characterize pesticide residues in groundwater and surface water, including biota and sediments, throughout Washington. Groundwater and surface water monitoring are being implemented as separate tasks; this paper addresses surface water issues only.

Objectives for the WSPMP include identification and quantification of pesticides in surface waters, documentation of trends in pesticide contamination, and assessment of adverse effects of pesticides on aquatic biota. Results will also be used to assess potential adverse effects on human health, and for the improvement of pesticide management in Washington state.

A total of 21 sites state-wide have been sampled for pesticides since 1992. Five surface water sites have been sampled in the Puget Sound basin (Figure 1); these are Mercer Creek near Bellevue, Thornton Creek in North Seattle, Sullivan Slough and Joe Leary Slough near Mount Vernon in Skagit County, and Fishtrap Creek near Lynden in Whatcom County. Mercer Creek and Thornton Creek receive urban drainage, and Sullivan Slough, Joe Leary Slough, and Fishtrap Creek are in agricultural areas. WSPMP surface water reports are available for 1992 (Davis, 1993) and 1993 (Davis and Johnson, 1994a).

Fish and sediment were collected from Mercer Slough and sediment from Sullivan Slough for the WSPMP in 1992. These data are available in a report by Davis and Johnson (1994b).

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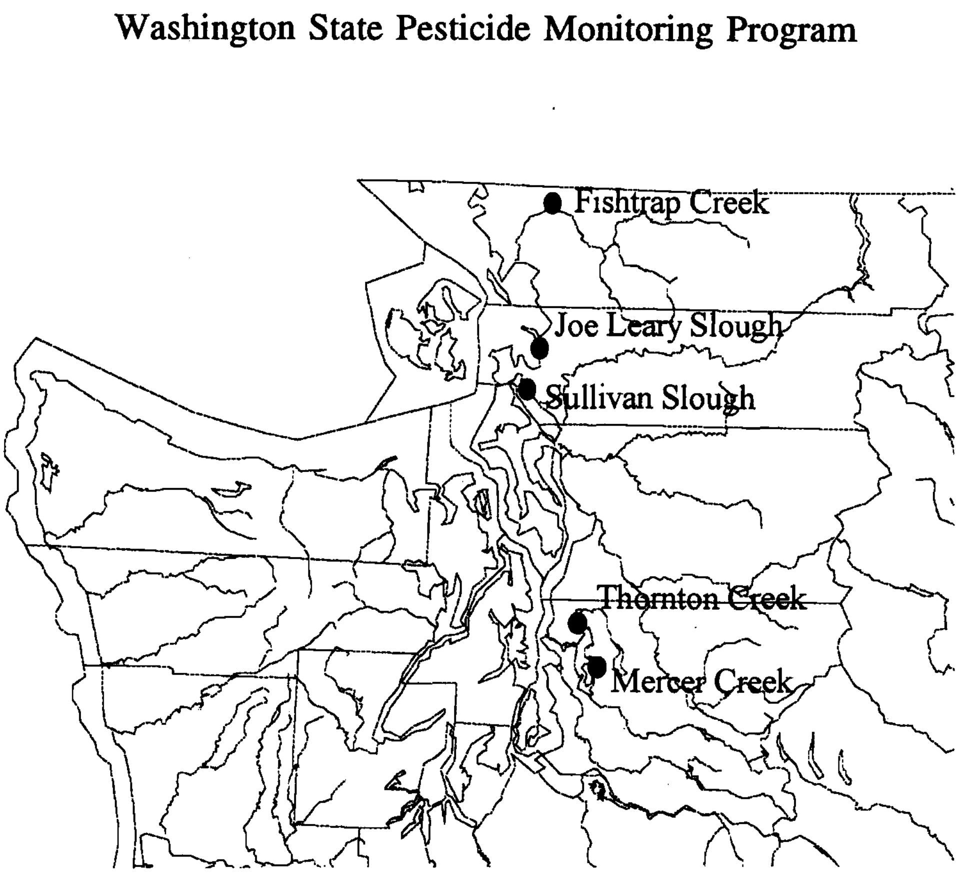

Figure 1. Surface water sampling sites in the Puget Sound basin, 1992-1994

METHODS

Sampling Design

High analytical expenses necessitate a simple screening survey approach for the surface water component. A single sample is collected at each site and is essentially used for a presence/absence assessment of pesticides with no indication of analyte variability. However, potential pesticide problems are identified primarily by comparing concentrations of detected pesticides to available water quality criteria. More intensive investigation is recommended for perceived problems.

Sampling frequency has been variable, depending on the funding available and the sampling objectives. Samples were collected only once in June of 1992 as a reconnaissance to refine methods. Sampling was expanded to four periods in 1993: April, June, August, and October. Budget restrictions in 1994 resulted in dropping the August sampling period. April and June represent the anticipated peak pesticide application periods. Sampling in October is scheduled to catch runoff from fall rains.

Surface water samples are analyzed for 162 pesticides and breakdown products in the following chemical groups: chlorinated pesticides, organophosphorus pesticides, nitrogen-containing pesticides, pyrethroid pesticides, chlorinated herbicides, and carbamates. Samples were also collected for total suspended solids (TSS), total organic carbon (TOC), conductivity, and nitrate+nitrite. Field measurements were taken at all sites for temperature, pH, and flow.

Sampling Procedures

Details of sampling procedures are outlined by Davis (1993). Procedures essentially followed those described in the Illinois EPA (1987) field methods manual. Briefly, samples were collected using U.S. Geological Survey (USGS) depth integrating samplers modified so that the water sample contacts only Teflon® or glass. Samples were hand composited, filling containers one-third full from each point in a quarter point transect across the streams.

Analytical Methods

Chlorinated, organophosphorus, nitrogen-containing, and pyrethroid pesticides were analyzed using a modified EPA Method 1618. Chlorinated herbicides were analyzed with EPA Method 615. Both methods use a gas chromatograph and an atomic emission detector. Carbamates were analyzed with EPA Method 531.1 using high-pressure liquid chromatography and post-column derivitization. All analyses were performed by Ecology's Manchester Environmental Laboratory.

Detection limits of pesticides for the WSPMP are substantially lower than those in other reports of water sampling data from Washington, and the target analyte list is larger. These analytical improvements are probably responsible for the higher number of pesticide detections for the WSPMP as compared to historical surveys.

QA/QC

Matrix spike and matrix spike duplicate (MS/MSD) and field duplicate samples were collected at one site per sample period to estimate analytical precision and accuracy. A transfer/bottle blank was prepared once per year to ensure that decontamination procedures are effective. Field spikes were prepared and submitted as blind duplicates to evaluate analyte loss and method accuracy and precision.

RESULTS

Twenty-four different pesticides have been identified in samples from the five sites in the Puget Sound Basin (Table 1). Five pesticides were detected exclusively at the urban sites, six exclusively at the agricultural sites, and 13 at both. Figure 2 shows the frequency of detection for the 24 compounds. DCPA (Dacthal) and 2,4-D, both herbicides, were the only pesticides found at all five sites.

In WSPMP samples collected in the Puget Sound basin, malathion was the only pesticide detected that has a Washington State or EPA aquatic life criterion. The concentration detected was below the criterion.

Three organophosphorus pesticides, diazinon, malathion, and mevinphos (Phosdrin), were detected at or above National Academy of Sciences (NAS, 1973) recommended maximum concentrations for protection of aquatic life and wildlife.

Site Evaluations

Mercer Creek drains the Bellevue area east of Interstate-405, including surface street runoff, into Lake Washington. Much of this area is residential, but includes a bridle trail park, shopping centers, schools, and two golf courses.

Mercer Creek has been sampled as an urban trend site once in 1992, four times in 1993, and three times in 1994. A total of 18 pesticides have been identified in these samples. This number of compounds has been equaled only by irrigation return flows in the Yakima Basin sampled for the WSPMP.

While criteria are available for nine of the 18 compounds detected at Mercer Creek, only two, diazinon and malathion, exceeded NAS recommended maximum concentrations for protection of aquatic life and wildlife. Both of these compounds are highly toxic organophosphorus insecticides that are heavily used in a number of applications, including several residential formulations. Detected concentrations approach acute toxicity values (i.e., within an order of magnitude) for some invertebrates (96-hour LC_{50} for malathion is 0.63-0.92 µg/L and 0.15-0.28 µg/L for diazinon (Johnson and Finley, 1980)).

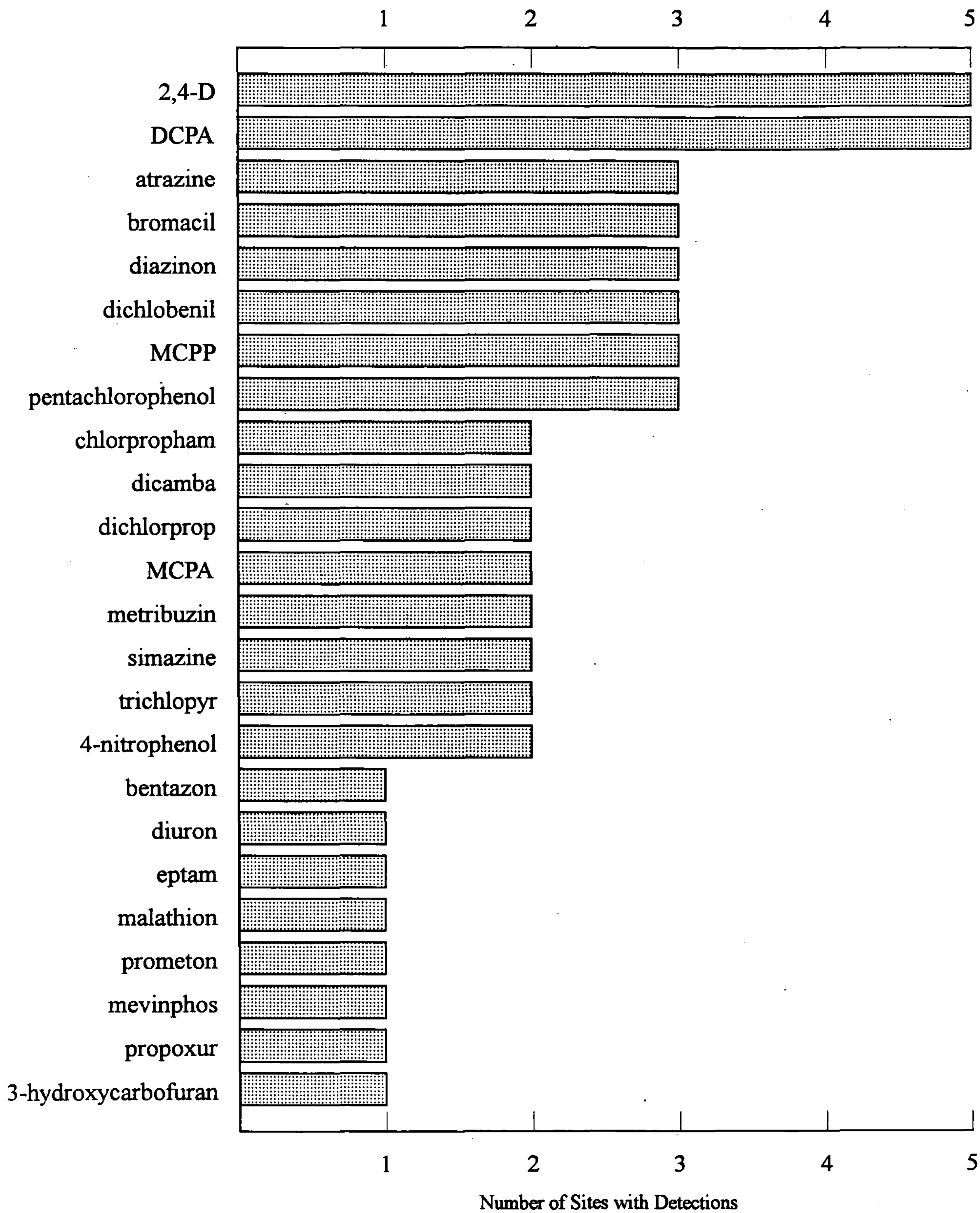

Figure 2. Detection frequency of pesticides in samples from the Puget Sound basin, 1992-1994

Only two pesticides, diazinon and 2,4-D, were detected in samples collected from Mercer Creek by the EPA in 1990 (PTI, 1991). Only seven of the 18 compounds detected in WSPMP samples were target analytes for the EPA study and for four of the seven, the EPA detection limits were higher than the concentrations reported for the WSPMP.

Thornton Creek also receives urban drainage. The creek flows through North Seattle on the east side of Interstate-5 picking up stormwater runoff from parts of Northgate, Paramount Park (including Jackson Park Golf Course), Pinehurst, Lake City, and Wedgwood; discharging into Lake Washington at Matthews Beach just north of Sand Point. Thornton Creek was sampled only once in 1992, detecting five pesticides. Diazinon was found at a concentration above the NAS-recommended maximum level.

Joe Leary Slough was sampled once in 1993 and three times in 1994. The slough drains the Olympia Marsh, northwest of Mount Vernon, into Padilla Bay. Water flow through the slough is influenced by tidal fluctuations, backing up behind tide gates at high tide. Land use adjacent to the slough is predominantly agricultural, and most of the slough has been channelized to drain fields.

Fourteen pesticides were detected in samples from Joe Leary Slough. The concentration of mevinphos, 11 µg/L, was more than 5,000 times higher than the NAS-recommended maximum concentration of 0.002 µg/L. Mevinphos is extremely toxic to aquatic invertebrates (96-hour LC_{50} for *Daphnia pulex* 0.13-0.25 µg/L) and fish (96-hour LC_{50} for rainbow trout 10.7-13.2 µg/L). Diazinon was also found at a level above the NAS-recommended limit.

Sullivan Slough is very similar to Joe Leary Slough in that it is also channelized, drains primarily agricultural land, and flows into Puget Sound through a tide gate. The slough drains much of Skagit Valley west of the Skagit River.

Sullivan Slough was sampled only once, in 1992. Six pesticides were identified. All were herbicides and none were above available water quality criteria.

Fishtrap Creek originates in Canada, flows through agricultural land used to grow dairy support crops and berries, through the northern edge of the town of Lynden, and into the Nooksack River. Groundwater monitoring in this area in 1988 (Erickson and Norton, 1990) detected five pesticides in well water samples. Samples for the WSPMP were collected once in 1992 and four times in 1993.

Eight pesticides were detected in samples from Fishtrap Creek. Seven of the detected compounds were herbicides and the eighth, pentachlorophenol, was a fungicide. None of the detected pesticides were above criteria or approached acutely toxic concentrations. None of the pesticides detected in groundwater samples were found in Fishtrap Creek.

DISCUSSION

The number of pesticides detected in samples from Mercer Creek indicate that pesticide contamination in urban stormwater is a potential threat to aquatic biota. The only site sampled by the WSPMP with similar numbers of pesticide detections is Moxee Drain in the Yakima Valley. Moxee Drain receives irrigation return water from some of the most intensively cultivated farm land in the state.

Although most pesticide concentrations in Mercer Creek and the other Puget Sound sites have been low, several compounds have been present consistently for the three years sampled. Chronic effects of most pesticides are unknown or poorly understood, especially for extended periods of exposure time. The number of pesticides detected per sampling event has been higher at Mercer Creek than other sites state wide. This may indicate that pesticide use in urban areas is more consistent throughout the year, thereby potentially increasing chronic effects.

With three or four samples collected per year at each site, detection of peak pesticide concentrations in stormwater runoff is not likely, but the high concentration of mevinphos found at Joe Leary Slough may be an example of such a peak. Undetected peak concentrations of other compounds may also be reaching levels that are acutely toxic to aquatic biota.

Table 1. List of pesticides detected at sites in the Puget Sound basin (1992-1994)

Pesticide Name	Mercer Creek*	Thornton Creek	Joe Leary Slough*	Sullivan Slough	Fishtrap Creek*
2,4-D	0.14	0.23	0.077	0.039	0.17
atrazine	0.025			0.24	0.04
bentazon			0.075		
bromacil	0.05			0.046	0.05
chlorpropham			3.0	0.10	
DCPA (Dacthal)	0.04	0.066	0.007	0.017	0.006
dicamba	0.013		0.036		
dichlobenil	0.11	0.054			0.035
dichlorprop	0.018	0.052			
diuron	0.19				
eptam			0.12		
MCPA	0.10		0.043		
MCPP	0.48		0.14		0.77
metribuzin			0.076	0.036	
prometon	0.058				
simazine	0.032				0.04
trichlopyr	0.054		0.019		
INSECTICIDES					
diazinon	0.07	0.077	0.017		
malathion	0.057				
mevinphos			11.0		
propoxur	0.047				
3-hydroxycarbofuran[1]			0.059		
4-nitrophenol[2]	0.18		0.084		
FUNGICIDES					
pentachlorophenol	0.015		0.075		0.008

* - Values are averages of detected pesticides from two or more samples (non-detects were not used in the calculations).
[1] - breakdown product of carbofuran.
[2] - breakdown product of parathion.

Effects from the 24 pesticides found in the Puget Sound area may be additive (Matthiessen, *et al.*, 1988), perhaps resulting in conditions that are lethal to aquatic life while the concentrations of individual compounds may not be a problem. Doull *et al.* (1980) have shown that mixtures of malathion with other organophosphorus pesticides are often synergistic.

Pesticides detected at all sites were predominantly herbicides, but only insecticides exceeded water quality criteria. Statewide, insecticides appear to be detected more frequently at agricultural sites.

The information gathered so far, although limited, is the only pesticide data available for many water bodies. Results from multiple years will identify pesticides that are a chronic problem. However, substantially greater effort will be required for more intensive sampling to achieve an adequate understanding of the occurrence and significance of pesticide residues in Puget Sound rivers and streams.

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