PUGET SOUND WATER QUALITY AUTHORITY

STATE OF THE SOUND
1986 REPORT

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Prepared with the assistance of:

Entranco Engineers, Inc.

July 1986

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1986 REPORT

KATHERINE FLETCHER
Chair

STATE OF WASHINGTON
PUGET SOUND WATER QUALITY AUTHORITY
217 Pine Street, Suite 1100 • Seattle, Washington 98101 • (206) 464-7320

July, 1986

To the Governor, the Legislature and other readers:

This is the first State of the Sound Report. It summarizes much of what is known about the Puget Sound basin--its history, economy, human population, land uses and other factors influencing its water quality.

This report is part of the preparation of a Puget Sound water quality management plan. Having begun work one year ago, the Puget Sound Water Quality Authority must adopt such a plan by January 1, 1987. We are part way toward this goal, having undertaken an extensive public involvement program, published nine issue papers, and held numerous formal and informal consultations with governments, organizations, experts and other individuals. An Advisory Committee and a Scientific Review Panel have been working with us throughout the process.

The State of the Sound Report helps lay the groundwork for the Puget Sound plan by summarizing the information upon which a plan must be based. It was prepared with the assistance of Entranco Engineers and a team assembled by them.

What is the state of the Sound? In the century since urbanization and industrialization of the Sound began, the Sound has been transformed from a relatively pristine body of water to the center of a bustling, heavily populated area. Human activity has damaged the Sound--from destroying over half its wetlands to contaminating its bottom sediments--at the same time that our lives have depended greatly on its tremendous productivity and beauty. Cycles of development have each taken their toll, but we have responded with actions to protect the Sound. Sewage treatment plants, industrial pollution control, the banning of certain chemicals, and regulation to protect wetlands and wildlife have each played a part in slowing degradation of the Sound.

Today, we need to take the next steps. Toxic contamination is severe in parts of the Sound, damaging plants and animals and posing long-term threats to the Sound's health. Because many toxicants persist essentially forever in the environment, and because we now understand how most contaminants stay in the sediments and are never "flushed" away, control and clean-up of toxic chemicals have become urgent tasks. In addition, bacterial and viral contamination have severely restricted the use of our shellfish resources. While these biological forms of pollution are not persistent like toxic chemicals, they are a growing problem because of our expanding population and our increasingly suburban patterns of development.

Looking ahead, we recognize that population growth in the Puget Sound basin will put additional strain on the health of the Sound. Perhaps the most significant challenge we face is to anticipate and prevent problems rather than waiting for them to happen.

This report does not provide the answers. We hope it will be a useful compendium of information leading to our next steps in preparing a Puget Sound water quality management plan.

We look forward to your interest and involvement as we take those next steps. We will be issuing a draft plan and environmental impact statement in September, which will be followed by an intense period of public review. Based on what we hear, we will prepare and adopt the final plan by the end of 1986. Please contact the Puget Sound Water Quality Authority (464-7320 or 1-800-54-SOUND) if we can be of any assistance to you.

Sincerely,

Katherine Fletcher
Chair

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INTRODUCTION

A century and a half ago the Puget Sound region was a forested wilderness, inhabited by Native Americans. Since then tremendous changes have taken place, both in the number of people and in the uses made of the area. Human uses of the land, air, and waters of the Puget Sound area affect the physical, chemical, and biological condition of the Sound.

Geographic Scope

In response to public concern about the condition of Puget Sound, the Puget Sound Water Quality Authority was established in 1985 to develop a Puget Sound Water Quality Management Plan. The plan will address short and long-term goals, and will include actions and priorities for clean-up and management of the Sound. Recognizing the many diverse activities and governmental responsibilities relating to the Sound, the plan will fill the need for a coordinated approach. This report is one step toward developing that plan. It discusses the natural characteristics of the Puget Sound area; the past, present, and likely future uses of the area, and the present condition of the area.

The Puget Sound Water Quality Management Plan will address Puget Sound south of Admiralty Inlet (including Hood Canal and Saratoga Passage), the marine waters north to the Canadian border, including portions of the Strait of Georgia, and the Strait of Juan de Fuca south of the international boundary with the province of British Columbia. The Puget Sound basin includes these marine waters and the entire land area that drains into them. This report addresses the entire Puget Sound basin (also referred to as the planning area) although in many cases data are only available for Puget Sound south of Admiralty Inlet. The total area of the basin is about 16,000 square miles, of which 80 percent is land and 20 percent is water (Figure 1).

Puget Sound Programs

A number of other programs are involved with Puget Sound water quality issues. Research by scientists in federal and state government, academic institutions, and consulting firms has lately focused on Puget Sound, generating a wealth of new information. The Puget Sound Estuary Program of the Environmental Protection Agency (EPA) and the Washington State Department of Ecology, in cooperation with other agencies, is engaged in a broad range of studies including identification of sediment contamination problems, design of monitoring programs, establishment of standard sampling and testing procedures, the determination of acceptable levels of sediment contamination, and the identification and review of chemicals that are of concern in Puget Sound. Ecology and EPA have also developed and implemented an urban bay program which is investigating and correcting contamination in several Puget Sound urban bays, including Commencement Bay and Elliott Bay. The Puget Sound Dredged Disposal Analysis, a cooperative study by the Corps of Engineers, the

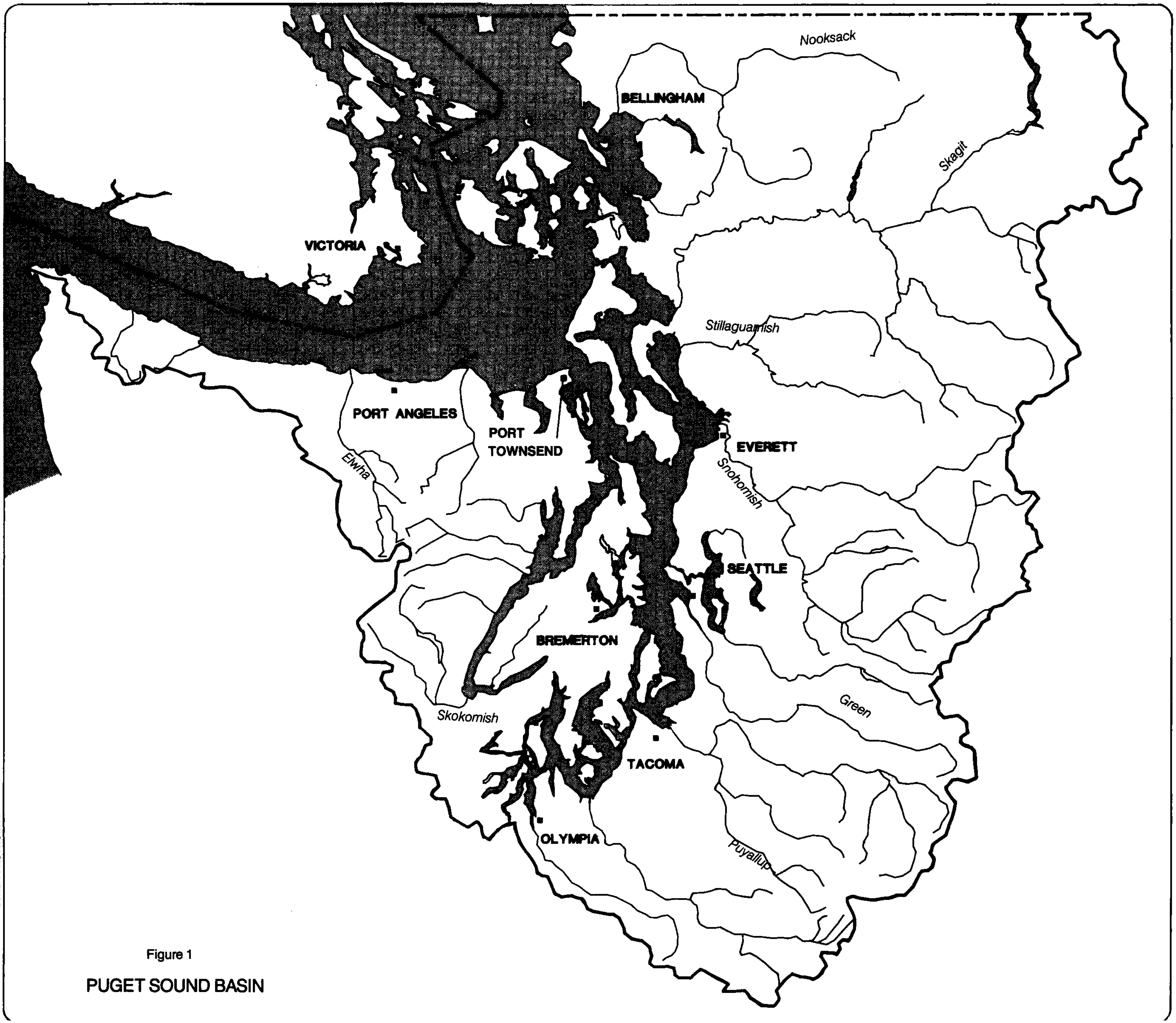

Figure 1

PUGET SOUND BASIN

Washington Departments of Natural Resources and Ecology, and the Environmental Protection Agency, is developing a revised program for the disposal of dredged material. Other studies and programs are being undertaken by agencies, local governments, sewer districts, and others.

PHYSICAL DESCRIPTION OF THE PUGET SOUND BASIN

ORIGIN OF THE BASIN

Puget Sound and the Strait of Georgia in British Columbia are inland arms of the Pacific Ocean that connect to the Pacific through the broad Strait of Juan de Fuca. Puget Sound south of Admiralty Inlet (including Hood Canal) is especially complex and consists of a set of interconnecting basins with diverse and highly productive habitats and marine life.

Tectonics

The shape of the valley containing the Sound, called the Puget Sound Lowland, emerged from very slow adjustments in the structure of the earth's surface. The surface of the earth consists of a solid crust that floats, like the shell of an egg, on softer material below. Stresses within the earth fracture this crust and set the pieces (called plates) moving about over its surface. These large-scale movements are known as plate tectonics.

About 200 million years ago a plate carrying what was to become North America broke loose from the plate that is now Europe and began heading west. The resulting gap became the Atlantic Ocean. The North American plate collided violently with plates forming the floor of the Pacific Ocean. That collision continues even today as evidenced in the mountain ranges and volcanos that extend from Alaska to California and southward.

Glacial Action

The form of the Puget Sound basin has been refined and detailed by the motions of glaciers over a period of nearly 100,000 years. During a series of ice ages, the climate of the earth cooled and tremendous ice sheets the size of whole states and several thousand meters deep built up on what is now coastal British Columbia. The ice spread out under the pressure of its own weight, and flowed south through what is now the Strait of Georgia and over much of the Puget Sound basin.

As the ice advanced, it scraped rock from its path and carried the debris southward; as the ice retreated during warming cycles, it deposited the material. Several shallow spots, called sills, that separate the sub-basins of Puget Sound are mounds of glacial debris. The ice last retreated about 10,000 years ago, leaving in its wake a mixture of sand, silt, cobble, and boulders, called glacial till, hundreds of meters deep over most of the lowland.

At one time, Puget Sound was a freshwater lake dammed on the north by the southern flank of the melting ice sheet and fed by the rivers of what is now western Washington. As the southern edge of the melting ice sheet moved north, the barrier between the lake and the sea was removed. Seawater

flowed into the depression left by the glacier and the Puget Sound marine system was formed.

SHAPE OF THE BASIN

The Strait of Juan de Fuca (see Figure 2 for place names) and the Strait of Georgia are each estuarine and are separated by a shallow ridge that breaks the water's surface as the San Juan Islands and forms sills in the passages between them. The Strait of Juan de Fuca is mostly deep open water, deepening from 300 feet (100 meters) in the east to over 650 feet (200 meters) as it joins the Pacific Ocean. There are two spots with depths in excess of 650 feet (200 meters) just north and west of the San Juans.

The shallow sill at Admiralty Inlet separates the rest of Puget Sound from the Straits. This portion of the basin contains approximately 38 cubic miles of water. The surface temperature averages 55^{o}F in summer and 45^{o}F in winter and has an average salinity of 27 parts per thousand. Deep water in the Sound is around 43^{o}F year around with a salinity of 30 parts per thousand.

Puget Sound south of Admiralty Inlet is divided into four sub-basins. The Main Sub-basin lies between the sills at Admiralty Inlet (sill depth: 220 feet or 66 meters) and the Tacoma Narrows (150 feet or 44 meters) and includes about 45 percent of the area and 60 percent of the volume of the four Puget Sound sub-basins. The deepest point (920 feet or 280 meters) is found off the city of Edmonds. Vashon Island occupies the center of the southern Main Sub-basin.

The Whidbey Sub-basin lies between Whidbey Island and the eastern mainland and includes Saratoga Passage and Port Susan. The Whidbey Sub-basin is not bounded by a sill and is deepest (over 650 feet or 200 meters) at Possession Sound, its point of connection to the Main Sub-basin. It shoals northward toward its narrow connections with Admiralty Inlet through Deception Pass and with Padilla Bay through the Swinomish Slough.

Hood Canal is a long, fairly straight sub-basin with a major bay at Dabob Bay and a sharp eastward bend at its head (Lynch Cove). It is set off from Admiralty Inlet by a 160-foot (50 meter) sill. Its deepest point is 600 feet (185 meters) in Dabob Bay, with depths up to 590 feet (180 meters) in the main canal.

The Southern Sub-basin is the most complex of the basins because of its many inlets and islands and its convoluted shoreline. Maximum depths are over 500 feet (188 meters) at the entrance to Carr Inlet and 360 feet (110 meters) at the entrance to Case Inlet, separated by a sill that is 100 feet (30 meters) deep. The southern inlets are the most shallow parts of the Sound and include large areas of tide flats.

The Puget Sound basin lies between the crests of the Cascades and Olympics and the lowland to the south (Figure 3). The elevation of the basin rim ranges from averages of 3,000 feet (in the south) to nearly 8,000 feet (in the north) along the Cascade crest and in the interior of the Olympics (Figure 3). The southern rim of the basin is lower and less clearly defined. Virtually all of the rolling lowland areas of the Kitsap Peninsula, islands, and mainland

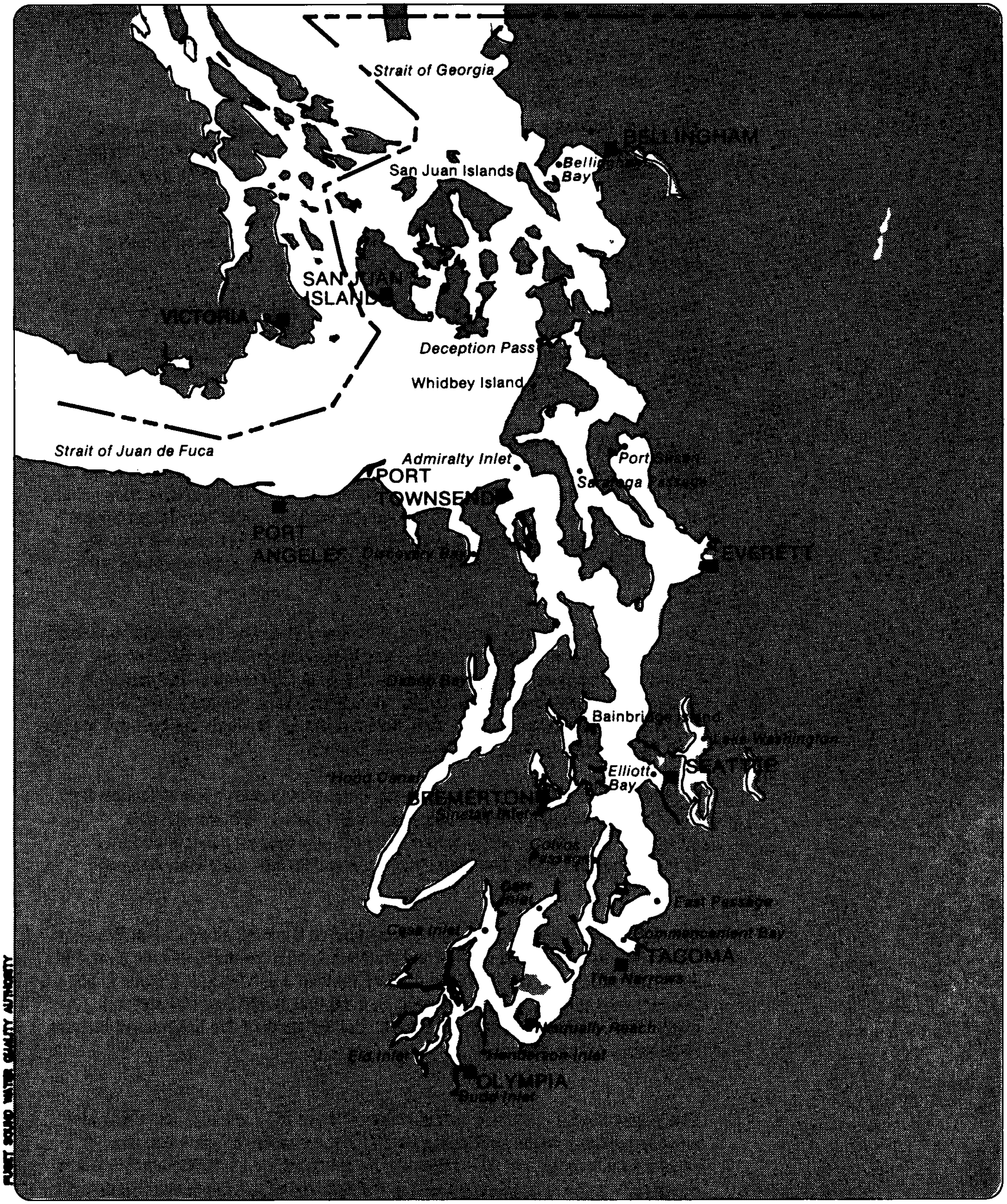

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Figure 2

PUGET SOUND LOCATIONS

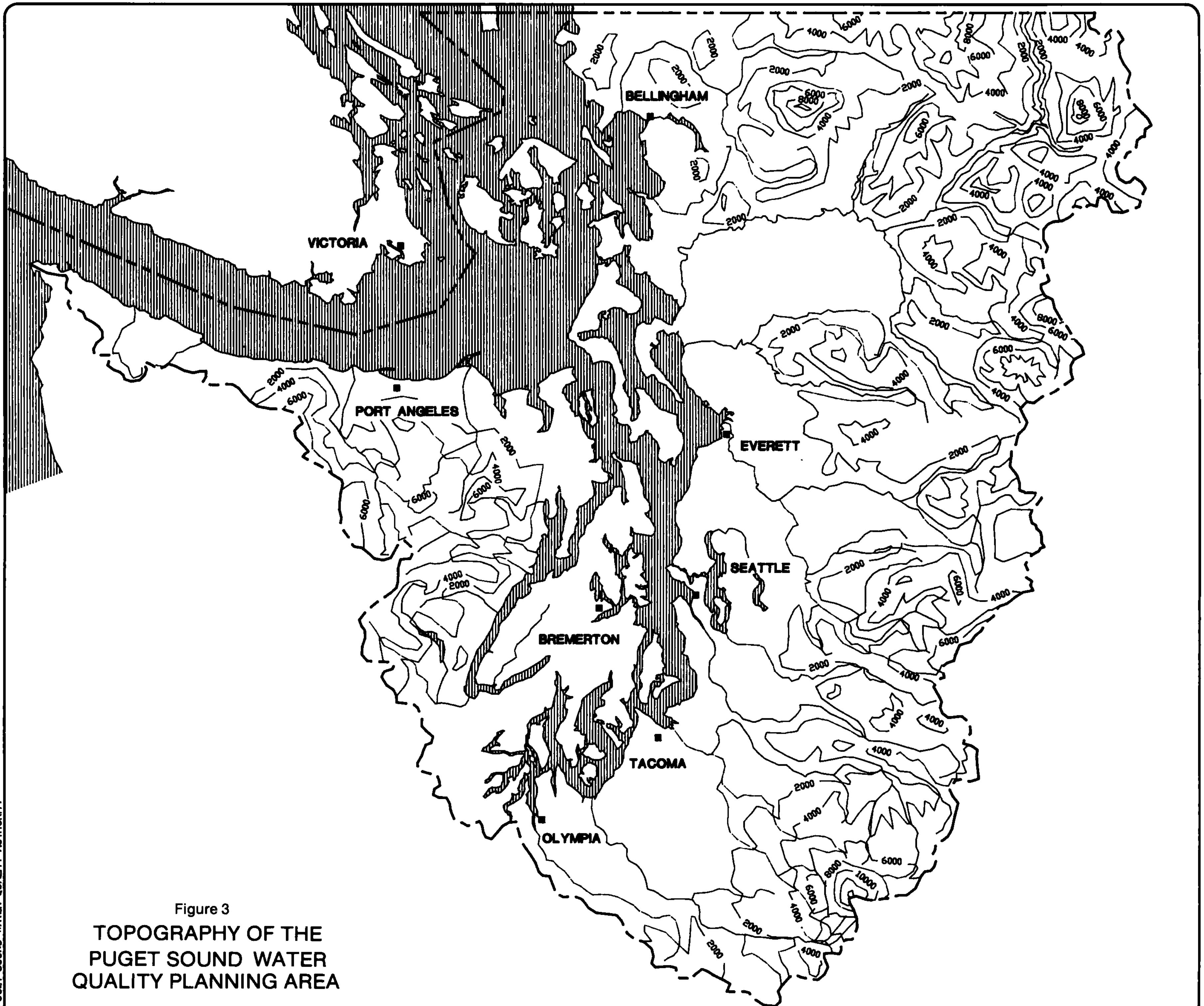

Figure 3

TOPOGRAPHY OF THE PUGET SOUND WATER QUALITY PLANNING AREA

which lie up to the foothills of the Cascades and Olympics are formed of and underlain by glacial deposits of clay, sand, and gravel. The formations of land along the shores of the Sound are primarily bluffs and beaches left by the retreat of glaciers and subsequently modified by erosion and deposition by rivers. Some pre-glacial rock formations crop out at sea level in the northern Sound region starting at Fidalgo Island and extending through the San Juans and to Chuckanut Mountain (Figure 4).

Along the western shore of Hood Canal, where elevations drop in a short distance from the heights of the Olympics to below sea level, there is only a narrow low strip of land along the water. Along the eastern flank of the Puget Sound lowland, river bottom and glacial deposits lie in valleys between extensions of the Cascade uplands. Pre-glacial elevations reaching over 2,000 feet in elevation are evident as far west as Tiger, Squak, and Cougar Mountains near the city of Issaquah.

Soils

Soils in the basin are generally poor due to their relative youth and their origin from glacial erosion. Mountain soils originate from the weathering of bedrock and contain little humus. Soils in the lowland have developed a higher organic content from several thousand years of forest growth. Older and relatively richer soils are found in the southern lowland that was less affected by glaciation. Drainage can be hampered in some areas by subsurface clay deposits, producing marshy or boggy soils. In other areas very rapid drainage through soils composed of sand and gravel can produce very dry soil conditions in spite of high rainfall. Overall, the natural lowland soils of Puget Sound are not well suited to agriculture but will support forests. The highest quality soils are found in the flood plains of rivers, especially in diked wetlands of high organic content such as those of the Skagit delta.

FRESHWATER RESOURCES

Since the marine waters of the Puget Sound basin are estuaries, their natural properties are strongly affected by the supply of fresh water. Fresh water flows to marine waters from a wide area called a drainage basin or watershed. Puget Sound is fed by a number of rivers, each with its own watershed. Combined, these watersheds form the Puget Sound basin.

Precipitation

Fresh water endlessly cycles between the ocean, the air, and the land in what is called the hydrologic cycle (Figure 5). Fresh water evaporates from the ocean, lakes, rivers, and the land and enters the atmosphere. This water returns to the land as precipitation. In the Puget Sound region, water enters the atmosphere over the Pacific Ocean and falls over the Puget Sound basin as rain and snow. Precipitation at measuring stations in the basin averages 23 to 96 inches (58 to 244 centimeters) per year, depending on location (Figure 6). The wettest places are the upper valley reaches of the western slopes of the Olympics and Cascades which strip the moisture from the ascending winds (estimates of up to 200 inches per year have been reported from the upper Nooksack Valley). The driest area in the basin is centered south of the San Juan Islands downwind of the Olympics. Approximately three-quarters of the year's precipitation falls between October and March (Figure 6) when storms out of the Gulf of Alaska strike the Puget Sound region about once every 20

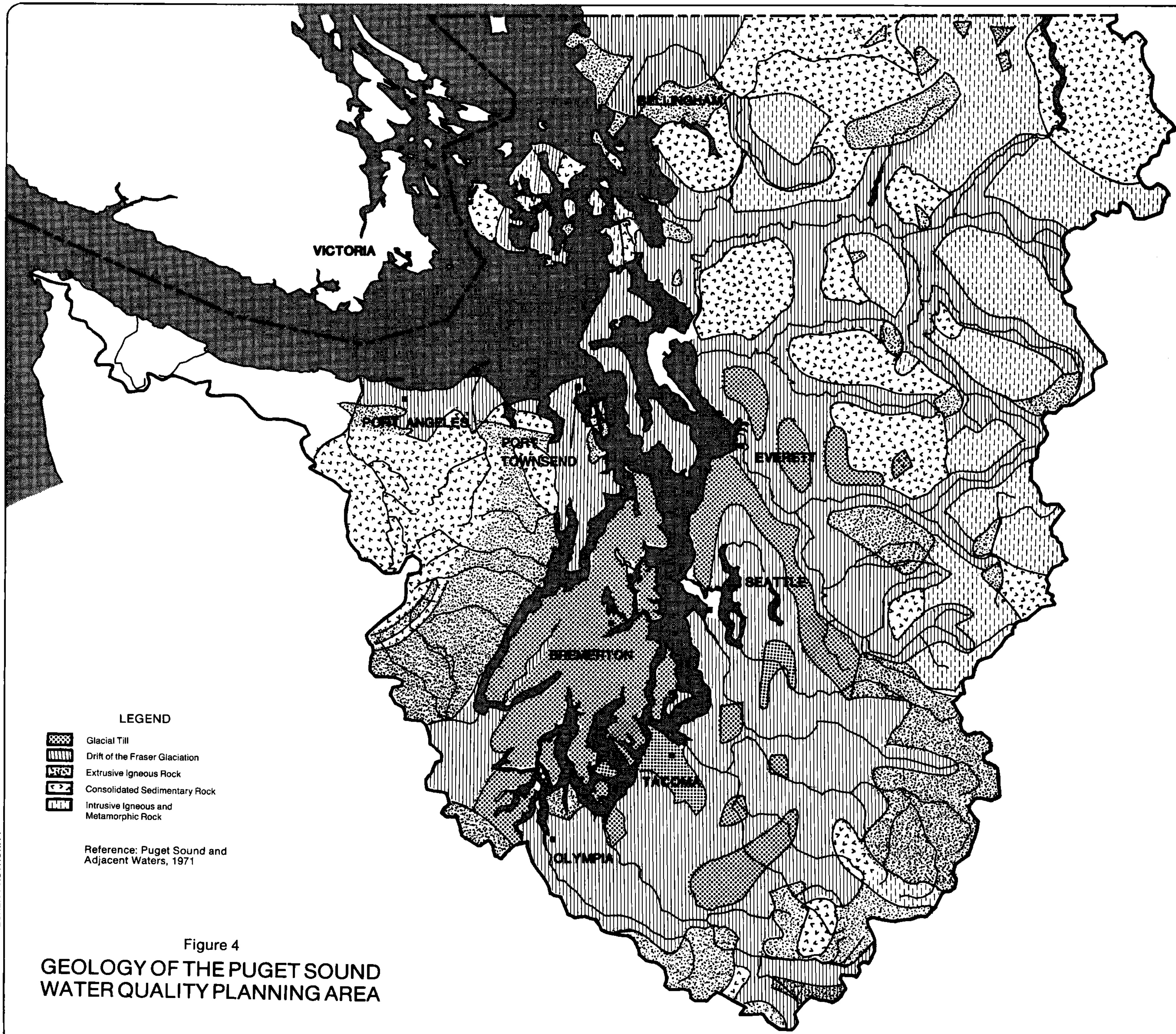

Figure 4

GEOLOGY OF THE PUGET SOUND WATER QUALITY PLANNING AREA

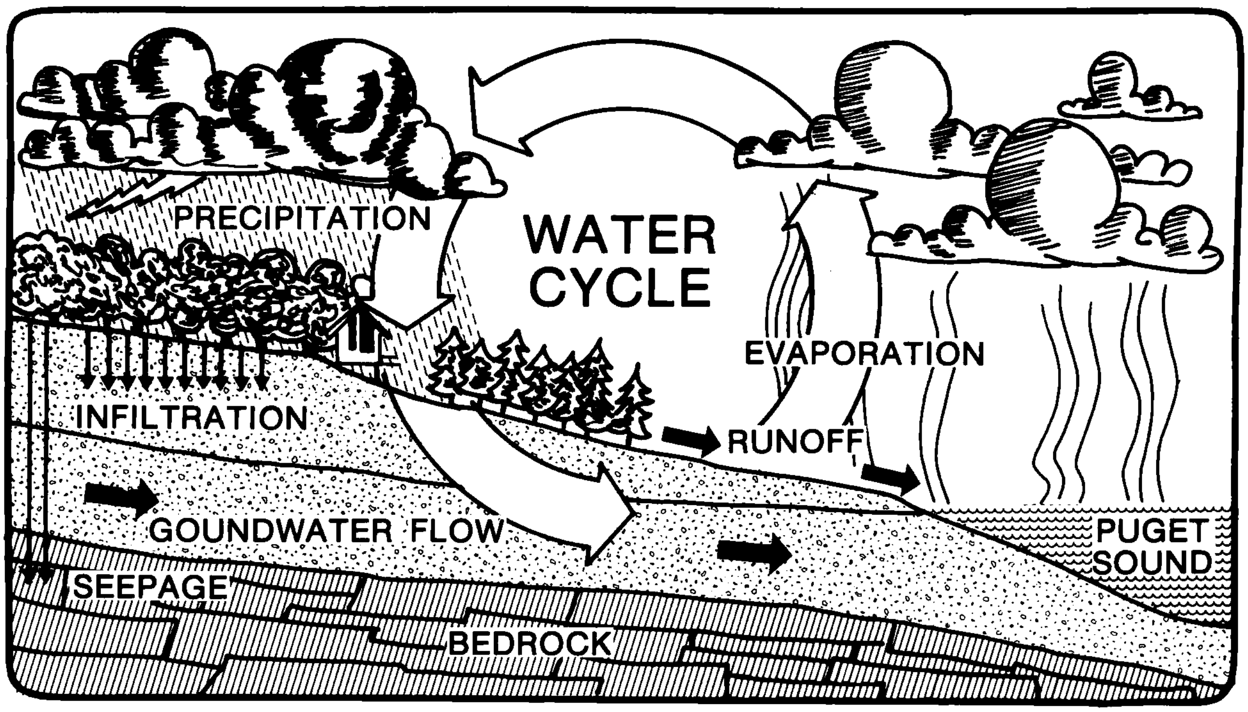

Figure 5

GENERALIZED DIAGRAM OF THE
HYDROLOGIC CYCLE

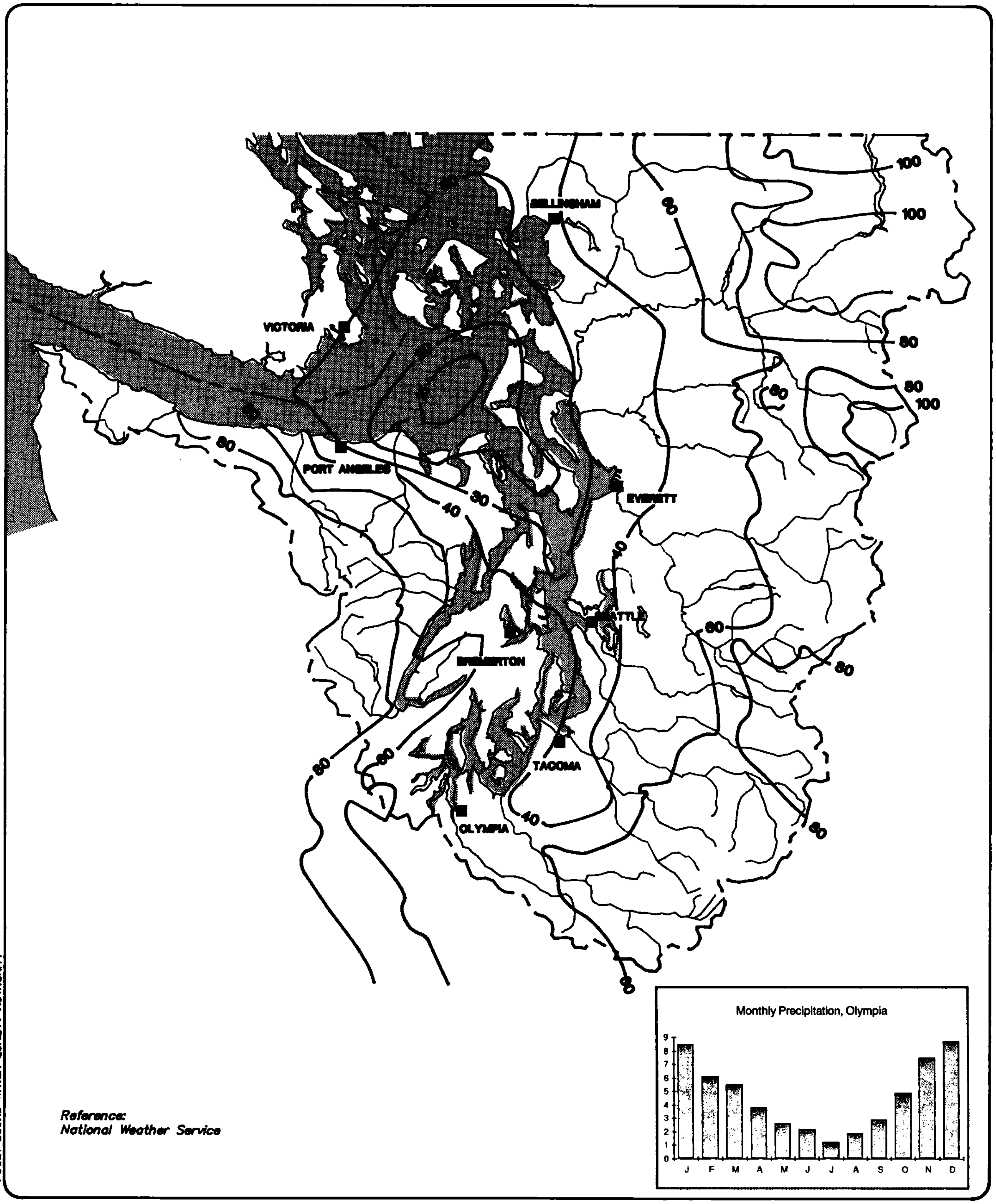

Figure 6

MEAN ANNUAL PRECIPITATION
OF THE PUGET SOUND
WATER QUALITY PLANNING AREA
(IN INCHES)

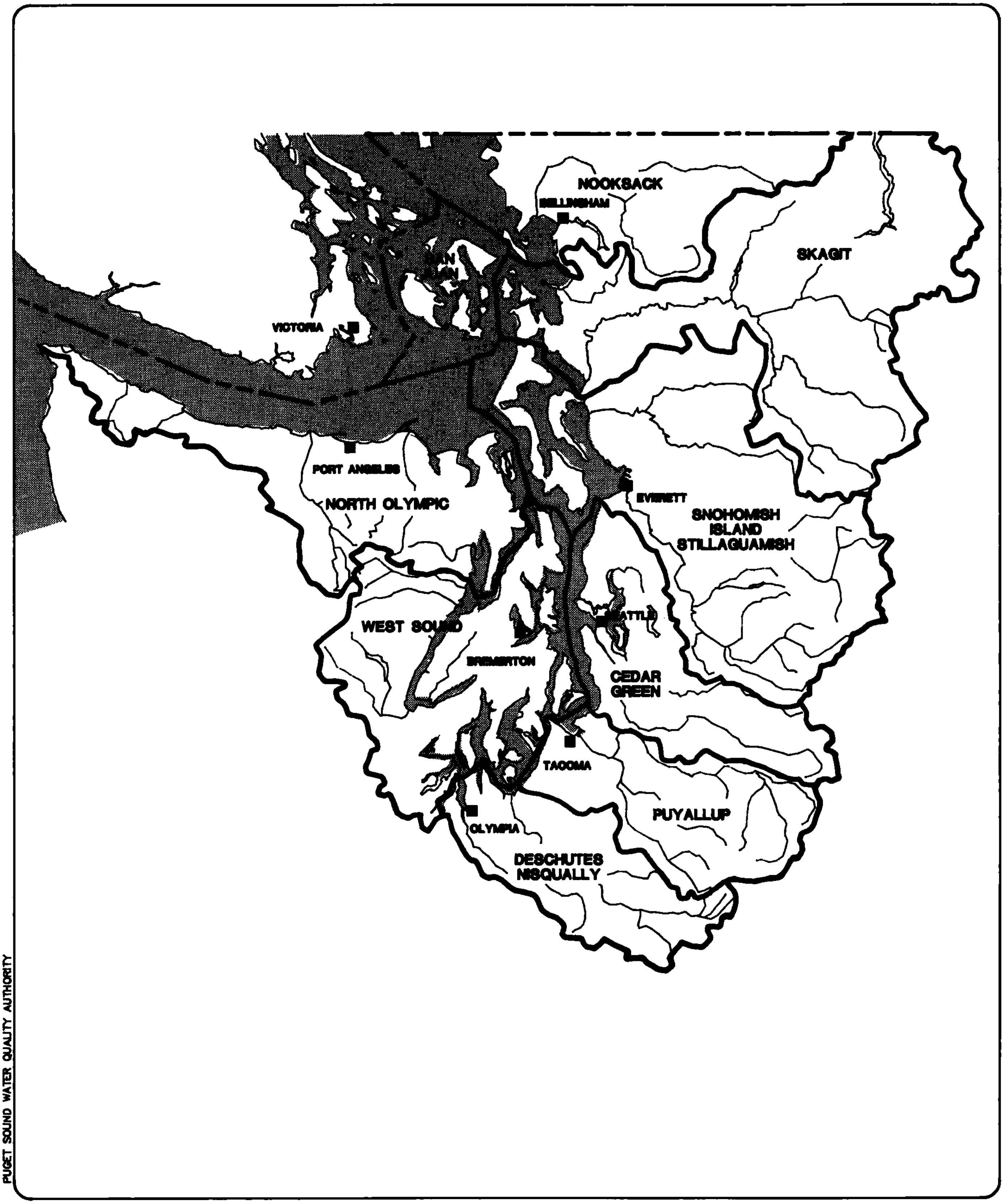

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Figure 7

CONSOLIDATED WATERSHED BASINS
OF THE PUGET SOUND
WATER QUALITY PLANNING AREA

to 50 hours, causing measurable precipitation about 16 days a month. During the summer the wind direction reverses and 30 days may pass without rain.

The topography of the watersheds and the types of vegetation that cover them determine the pattern of streams, rivers, lakes, and wetlands that carry fresh water to the Sound. Department of Ecology water resource managers have divided the Puget Sound basin into nine "Consolidated Planning Area Basins" (Figure 7) based on river systems: Nooksack/Sumas, Skagit, Stillaguamish/-Snohomish, Cedar/Green, Puyallup, Nisqually/Deschutes, San Juan, North Olympic, and West Sound. These watersheds vary in size from 112,500 to 1.95 million acres (455 to 7890 square kilometers).

Precipitation is delayed in reaching the Sound by its transit through various reservoirs of fresh water. For example, above an elevation of about 2,500 feet, snowfields and glaciers store a considerable amount of fresh water. Storage in snowfields is usually for a maximum of six months, but glaciers can store large quantities of water for years or decades. In the Skagit River basin alone there are 396 glaciers covering an area of 64.4 square miles (165 square kilometers). Each square mile of glacier produces approximately 9,000 acre--feet (a volume of water that will cover 9,000 acres of land to a depth of one foot) of streamflow each year. Skagit glaciers thus release about 580,000 acre-feet (0.7 cubic kilometers) of water annually.

Precipitation also is stored temporarily in other surface reservoirs--soils, streams, rivers, lakes, and wetlands. A portion of this water evaporates back to the atmosphere or is transpired (breathed out) by plants. The rate of return depends on a number of factors including the amount of water present, wind speed, temperature of the air and water, amount of sunlight, and land covered by plants. A portion of the precipitation soaks deep into the earth and becomes groundwater, much of which returns to Puget Sound through streams, rivers, and underground flows.

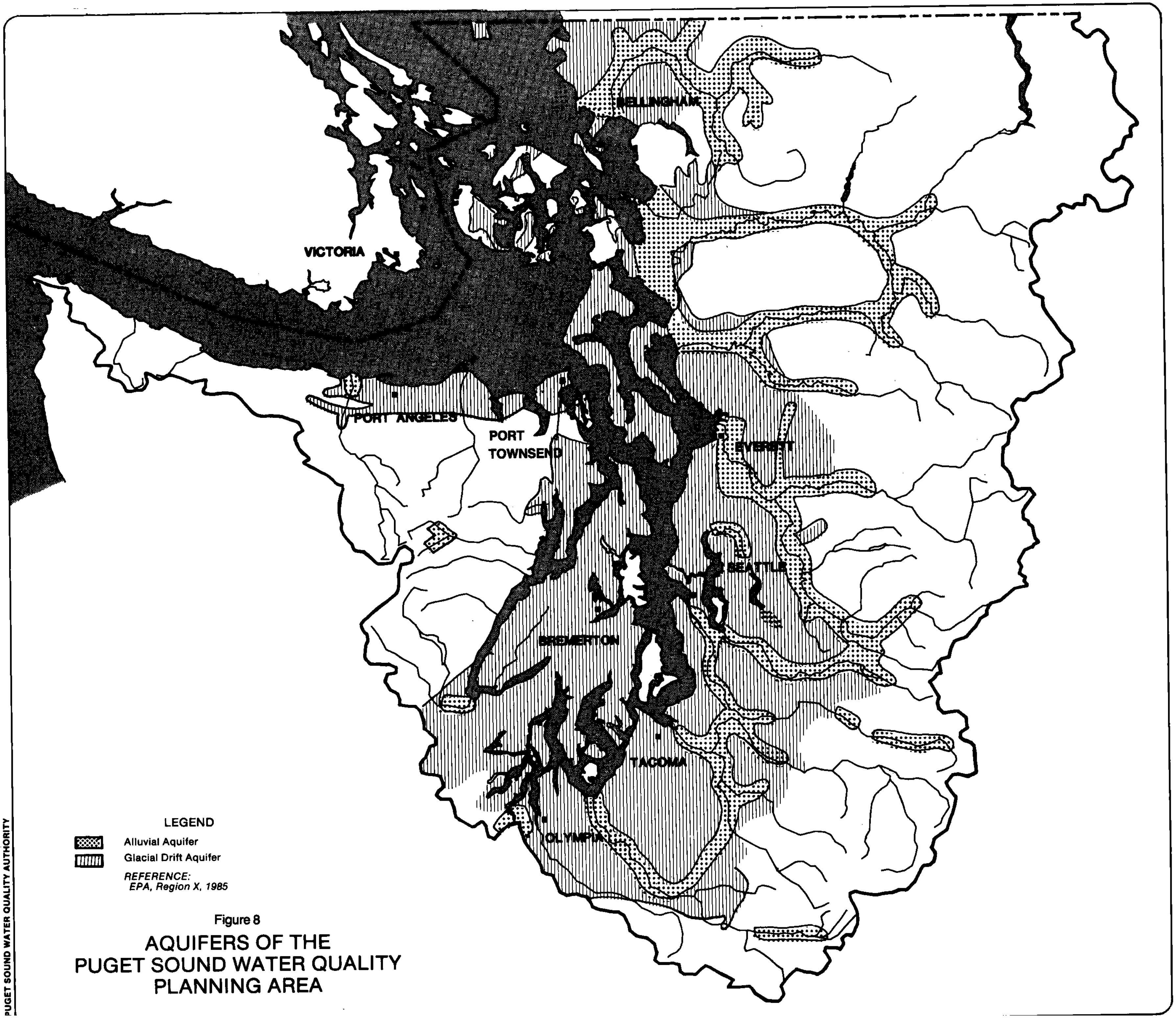
Groundwater

Groundwater is water in porous underground deposits, forming reservoirs known as aquifers (Figure 8). Most of the groundwater found in the Puget Sound region exists in sandy sediments deposited by streams and glaciers. Groundwater is used extensively in the Puget Sound basin for drinking and irrigation and for animals. Its quantity and quality must be protected.

The sustainable yield of water from an aquifer ultimately is determined by the rate at which surface water soaks through soils and streambeds to recharge it. At present the total extraction of groundwater for human uses in the Puget Sound basin has not exceeded the rate of recharge, although groundwater extraction apparently has caused some saltwater intrusion in the San Juan Islands and elsewhere. The groundwater recharge rate for the Whidbey/-Camano watershed is approximately 6,000 acre-feet (7.4 million cubic meters) per year, while the Nisqually watershed recharges at the rate of 200,000 acre-feet (246.7 million cubic meters) per year.

Lakes

There are over 2,800 lakes and ponds covering a total of 175 square miles in the Puget Sound basin, ranging from small, cold alpine lakes to larger lakes in



LEGEND

Alluvial Aquifer

Glacial Drift Aquifer

*REFERENCE:
EPA, Region X, 1985*

Figure 8

AQUIFERS OF THE PUGET SOUND WATER QUALITY PLANNING AREA

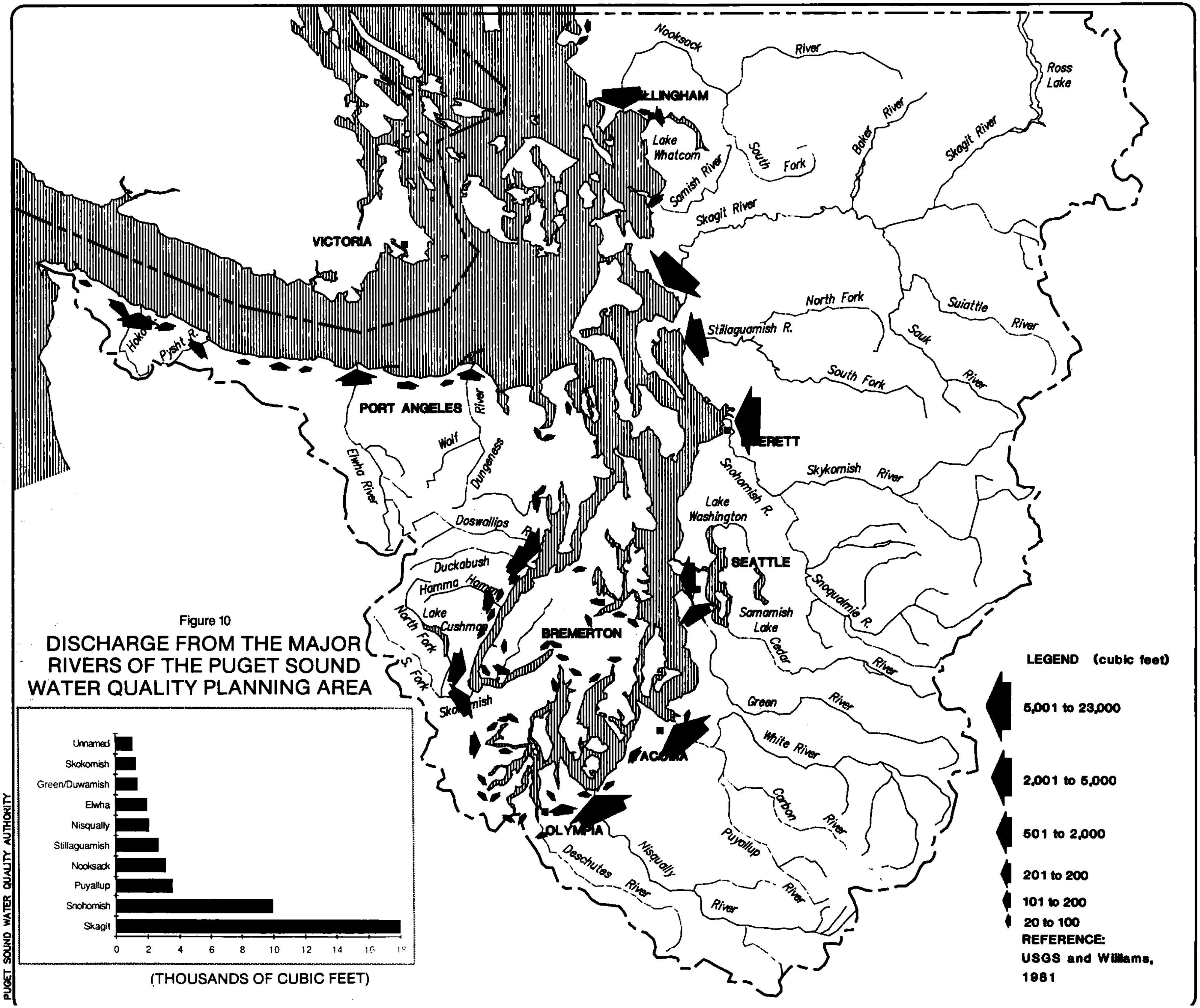


Figure 10

DISCHARGE FROM THE MAJOR RIVERS OF THE PUGET SOUND WATER QUALITY PLANNING AREA

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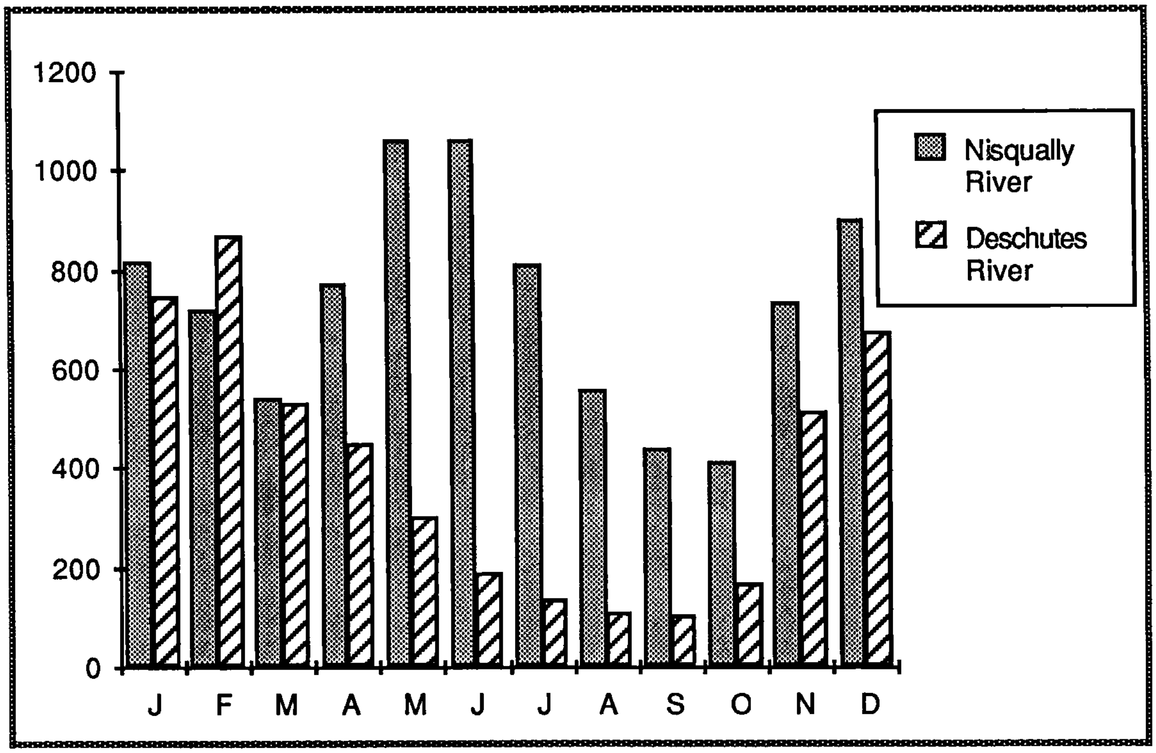
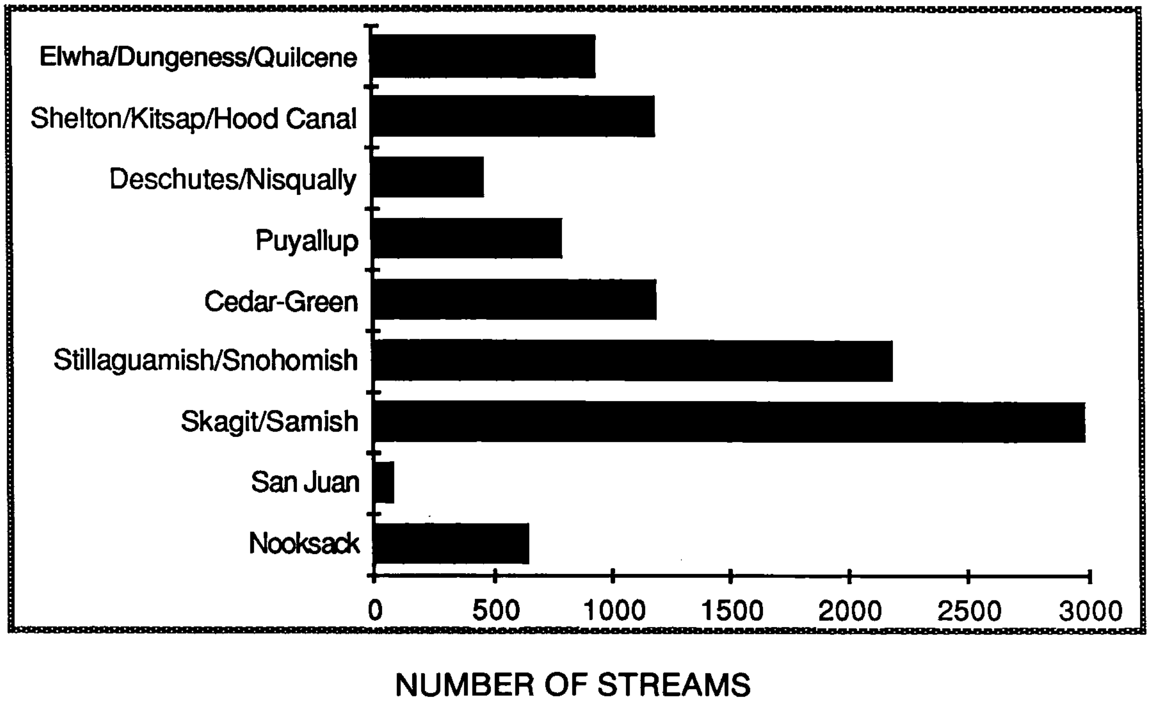


Figure 11

AVERAGE MONTHLY FLOWS FROM THE NISQUALLY AND DESCHUTES RIVERS

(cubic feet per second)

Reference: USGS



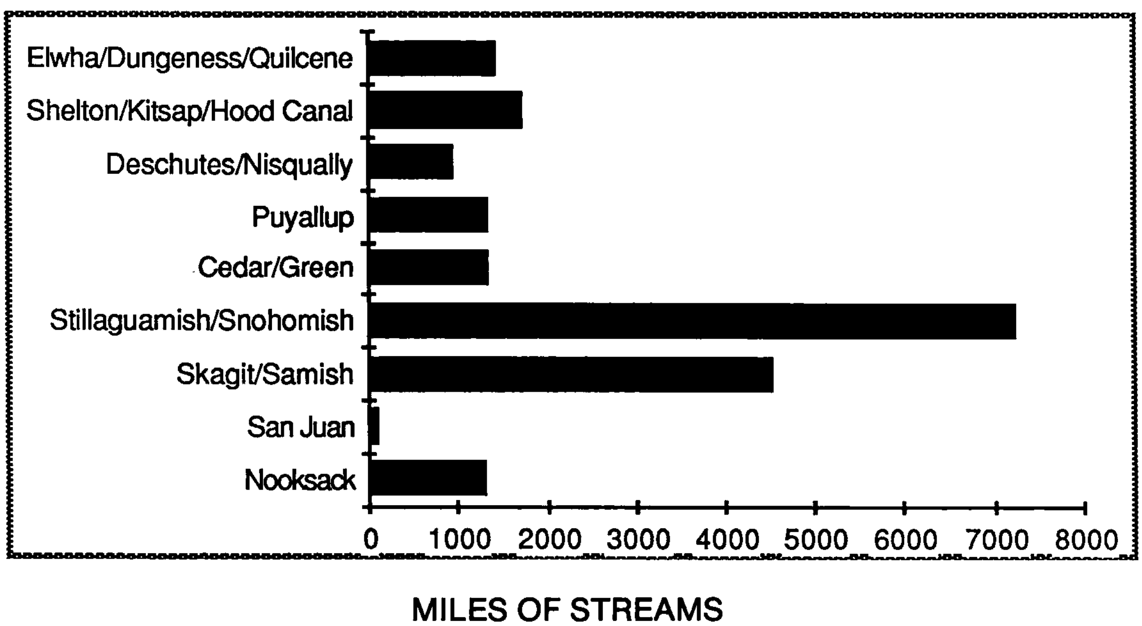


Figure 9

STREAMS IN THE PUGET SOUND
WATER QUALITY PLANNING AREA
BY WATERSHED

lowland valleys. There are also 24 major dam-created reservoirs in the basin with a total surface area of 70 square miles.

Rivers

Over 10,000 rivers and streams stretching over 16,000 miles have been catalogued in the Puget Sound basin (Figure 9). The flows of most of these streams are not separately measured. There are more than 75 river systems draining into Puget Sound with average annual discharges ranging from 20 to 18,000 cubic feet (0.6 to 510 cubic meters) per second (Figure 10). The total average annual addition of fresh water to the marine waters of the Puget Sound basin is about 45,000 cubic feet per second (1250 cubic meters per second). This adds up to approximately 27 million acre-feet or 9.5 cubic miles per year. Eight major rivers account for more than 80 percent of the total amount of fresh water entering Puget Sound. Many small streams also flow directly into the Sound. In addition, the Fraser River in British Columbia discharges a quantity of fresh water into the Strait of Georgia that exceeds the total runoff into the entire Puget Sound basin.

There are two typical patterns of seasonal river flow in the basin. The smallest streams drain the smallest area. Their flow rates follow the pattern of rainfall with maximum flows in winter and during rainstorms. This pattern is seen in the Deschutes River and other streams that drain the southern and western lowlands of the basin (Figure 11). In most rivers, however, there is a delay between precipitation in the watershed and resulting flows into the Sound. Water from mountain areas that falls as snow in winter is stored as snow or ice until spring or summer and must then travel some distance before entering the Sound. Thus most rivers which have maximum flow rates in winter have a second, smaller peak flow in late spring from melting snow. A good example is the Nisqually River. It has a late spring peak fed by high--altitude late-season glacial melt (Figure 11). A third pattern is represented by the Fraser River, fed by the vast British Columbia ice fields. The volume of its discharge to the Strait of Georgia during June and July exceeds the rain-fed winter flow.

Freshwater Flows to Puget Sound Sub-basins

The freshwater flows reaching each of the four major sub-basins of Puget Sound differ because of the size and nature of the watersheds that drain into each basin. Sixty percent of the total fresh water entering the Sound flows into the Whidbey Basin from the drainage of the three largest rivers in the planning area--the Skagit, Stillaguamish, and Snohomish. These rivers collectively drain about 50 percent of the planning area. The Main Sub-basin receives 20 percent of the fresh water entering the Sound from the Puyallup, White, Green, Sammamish, and Cedar Rivers. No major rivers flow into Hood Canal, but it receives 10 percent of the fresh water entering the Sound through minor rivers (Skokomish, Dosewallips, Duckabush, Hamma Hamma, and an unnamed river) and some smaller streams draining the eastern Olympic Peninsula. The Southern Basin receives less than 10 percent of the drainage into the Sound even though it has a large drainage area. It is fed mostly by small rivers and streams (the only major river is the Nisqually), and snow and rainfall amounts are lower in this less mountainous watershed.

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Figure 12

BOTTOM SEDIMENTS
OF PUGET SOUND

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Figure 13

GENERALIZED SURFACE WATER MOVEMENT AT FLOOD TIDE IN PUGET SOUND

SEDIMENT IN THE SOUND

Transport

The faster water moves, the larger and heavier the particles it can carry and the farther it can transport particles of various sizes before they sink to the bottom. The smaller and lighter a particle, the more slowly it sinks and the farther it is carried. Sediments are classified by their size. Clay and silt have the smallest grains. Mud particles are a little larger, and sand is larger yet, followed in increasing size by gravel, cobbles, and boulders. The type of sediment at a given location is a direct indication of the strength of currents and mixing in the waters above. Coarse sediments are usually found below areas of fast-moving water, and fine sediments are found beneath slow-moving water.

Distribution

Many types of sedimentary deposits are found in Puget Sound (Figure 12). Muddy sediments in the Sound are found where water is the stillest: in the deepest basins, in the quiet upper reaches of protected bays, and along shores with little wave action. Coarse sand and gravel deposits are found on the tops of sills, in narrow passages, and on exposed beaches where swift currents and heavy surf carry away lighter particles. River water carries a natural load of suspended sediment, derived from erosion of soils and rock. The river's speed decreases as it enters Puget Sound, and the suspended load settles to the bottom, heaviest and largest particles first. Thus, bottom sediments become finer and finer as distance from the mouth of the river increases. Large rivers with heavy loads of sediment such as the Skagit build huge deltas out into the bays they enter (Table 1). Also important as a source of sediment (especially sand and gravel) is the erosion of beaches and bluffs along the shoreline. The shorelines are largely composed of very loosely bound glacial deposits. Additional sediment--mostly mud--is formed of detritus, the waste products and debris of living organisms in the Sound.

Deposition

There have been a number of measurements of rates of sediment deposition and accumulation in Puget Sound, but natural variations over time and from place to place make generalizations about sediment accumulation difficult. Tidal currents carry sediment, creating some scoured areas where little or no sediment is deposited and other areas where large amounts of sediment are deposited. Measurements of sediment in the Main Sub-basin, made by dating a radioactive isotope of lead in core samples of bottom sediments, show that approximately 0.18 to 1.20 grams of sediment accumulate in a year on one square centimeter of the Sound's bottom (one-twentieth to two-fifths of an inch). All but a tiny organic fraction comes from rivers and shoreline erosion.

Functions

Sediments perform many important functions in the marine system. They form the habitat for bottom-dwelling (benthic) organisms and affect the fate of contaminants in the Sound. Organic detritus in nearshore and deep sediments supports a major branch of the food web of the Sound. Sediment introduced by runoff from land through rivers, streams, and groundwater can introduce chemicals, nutrients, and bacteria into the Sound because these contaminants often are carried by particles.

TABLE 1: SEDIMENT DISCHARGE RATES FOR MAJOR RIVERS

River	Annual Sediment Discharge (billion pounds/year)
Skagit	2.4
Snohomish	1.4
Duwamish	0.4
Puyallup	1.0
Stillaguamish	0.9
Nisqually	0.4
TOTAL	6.5

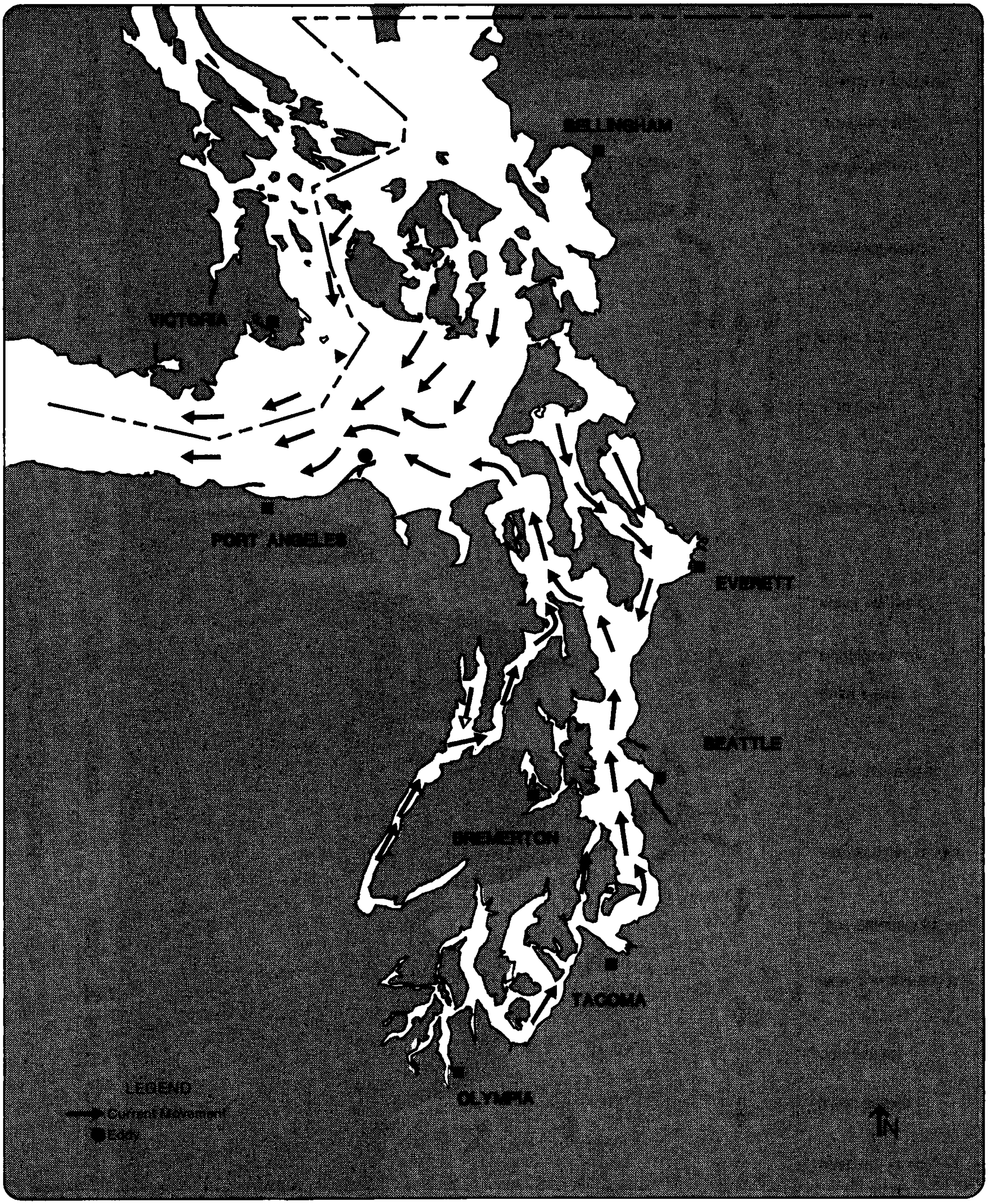
ESTUARINE CIRCULATION

Flow Pattern

Estuaries have a distinct pattern of water movement created by the action of the tides and the presence of fresh water. Since estuaries are extensions of the ocean, they are affected by the tides which pump large volumes of water back and forth, in and out of the basin. The tides flood inland and ebb seaward twice a day in Puget Sound (Figures 13 and 14). Tidal currents extend from the surface to the bottom and are the strongest currents in the Sound.

Fresh water is lighter, or less dense, than saltwater and tends to float and flow over the top of seawater. As it does this, some of the saltwater is mixed up with the freshwater, creating a brackish (less salty) layer at the surface (about 30 to 130 feet or 10 to 50 meters deep in the Puget Sound region). This surface layer flows seaward under the force of gravity, eventually reaching the Pacific Ocean. To replace the seawater in the deep layer which was mixed into the surface layer, more seawater is drawn into the estuary from the ocean. This characteristic estuarine circulation--seaward at the surface and landward below--exists throughout Puget Sound and the Straits of Georgia and Juan de Fuca (Figure 15). Seawater from the Pacific moves up the Strait of Juan de Fuca, enters Admiralty Inlet, and flows south through the depths of the Sound.

The two-layered circulation pattern is complicated in Puget Sound by the presence of various islands and channels. Eddies or whirlpools appear during strong tidal action (larger eddies are noted on Figures 13 and 14). The blocking effect of Vashon Island disrupts the two-layered flow pattern in East Passage, where currents at all depths are generally to the south, and in Colvos Passage, where currents are generally to the north. The sills that divide the sub-basins of the Sound also disrupt the two-layered flow pattern, and the shallow waters at these locations are strongly mixed by the tides. As salty deep water enters the Sound, some of the brackish surface water is mixed into the deep layer and recycled in the basin (Figure 15). Some of the surface water from the Puget Sound Main Sub-basin also enters Hood Canal and Saratoga Passage. In fact, as much as one-half to two-thirds of the outflowing surface water from the Puget Sound Main Sub-basin is diverted before going through Admiralty Inlet, and as much as one-third to one-half makes a submarine return trip through the depths of the Main Sub-basin instead of



PUGET SOUND WATER QUALITY AUTHORITY

Figure 14

GENERALIZED SURFACE WATER MOVEMENT
AT EBB TIDE IN PUGET SOUND

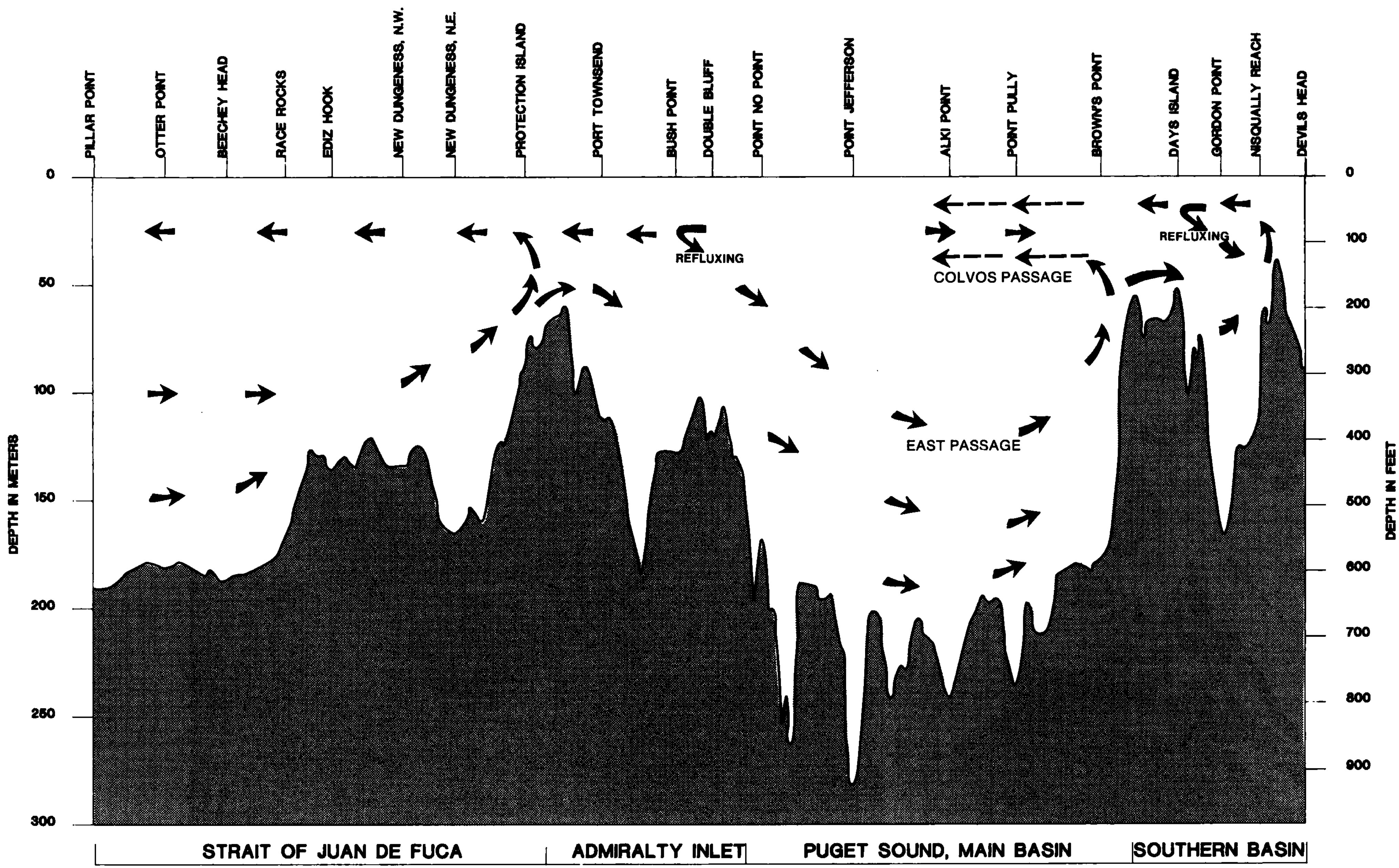


Figure 15

GENERALIZED VERTICAL CROSS-SECTION SHOWING NET CIRCULATION IN PUGET SOUND

exiting to the Strait. The same type of pattern can be inferred in the other sub-basins set off by sills.

Exchange with the Ocean

An important physical characteristic of an estuary is its ability to exchange its water with that of outside waters. It is a natural process that renews the depths and purges the surface. Exchange helps prevent the deep basins of the Sound from becoming naturally stagnant from organic decay, using up their oxygen and turning anoxic--something deep fjords with shallow sills tend to do. Exchange also plays a critical role in governing the fates and effects of contaminants that enter Puget Sound. It has the ability to carry dissolved waste products out to sea. In Puget Sound south of Admiralty Inlet the diversion and remixing of surface water mentioned above severely limits the amount of exchange. Puget Sound is not a pipe or open drain that will carry dissolved or suspended contaminants directly out to sea. The process is short-circuited by the recirculation of surface water. Fresh water on the surface of the Main Basin takes about a week to get from the mouth of the Duwamish River to the Admiralty Inlet sill. Then much of it spends an additional 10 days going back to its starting point. It must make the trip twice, on the average, before reaching the Strait of Juan de Fuca.

Exchange is obstructed even more by the complexity of the Sound's waterways. The tides slosh water back and forth between basins, recirculating it within the Sound and only slowly carrying it out to sea. Any contaminants carried by the water also spread throughout the Sound before exiting to the Strait. The time for the water in a single sub-basin of the Sound to be replaced can be measured in days or weeks. The length of time that water resides in the whole system of basins is measured in months.

Figure 16 illustrates a simulation performed on a computer model of the Sound in which 400 tiny "parcels" of water are released in East Passage and tracked as they are transported by currents. The computer estimated the motion of each parcel. By counting the number of parcels remaining at various times after discharge, the percent of the water that has been retained in the Sound is estimated. After three months almost half of the parcels of water are still in the Sound. After six months 25 percent remain, and after 12 months five percent remain.

Trapping of Particles

Estuarine circulation also controls the fate of the tons of sediment delivered by river water and other sources. Particles initially suspended in the surface water settle into the deeper layer. Once they enter the deep layer, they are carried back inland. Since even very fine particles can settle through the brackish surface water layer faster than they are carried out to sea, estuaries characteristically retain particles. Perhaps one to five percent of sediment particles initially in the surface waters of the Puget Sound Main Basin are carried out through Admiralty Inlet; the rest are trapped in the Sound. The straits in the Puget Sound basin also exhibit estuarine circulation and therefore retain particles. Since some contaminants bind to particles, the ability of the waters of the Puget Sound basin to carry those contaminants out of the basin to the ocean is very limited.

HABITATS OF THE PUGET SOUND BASIN

The complex network of bays, channels, and waterways in Puget Sound, and the surrounding lowlands and uplands, support a wonderful variety of plants and animals in different habitats. A habitat is a physical environment with specific ecological conditions that enable it to support particular populations and groupings of organisms. Characteristics that distinguish one habitat from another, either on land or in water, include whether the soil or sediment is coarse or fine, its chemistry, the temperature range, and exposure to wind, waves, and currents. The interactions between a physical habitat and its typical flora and fauna are complex. A typical nearshore habitat range in Puget Sound is illustrated, along with characteristic plants and animals in Figure 17.

In all environments, organisms can be arranged in a network called a food web, the strands of which join animals to their sources of food. A generalized food web for the marine environment is shown in Figure 18. The first source of food is the growth of plants which are called the primary producers. The animals that are supported by primary producers are consumers. Animals that eat only plants are called herbivores, those that eat only other animals are carnivores, and those that eat both plants and animals are omnivores. An additional food source for many animals is dead organic matter (detritus) from plants and animals which is broken down by bacteria.

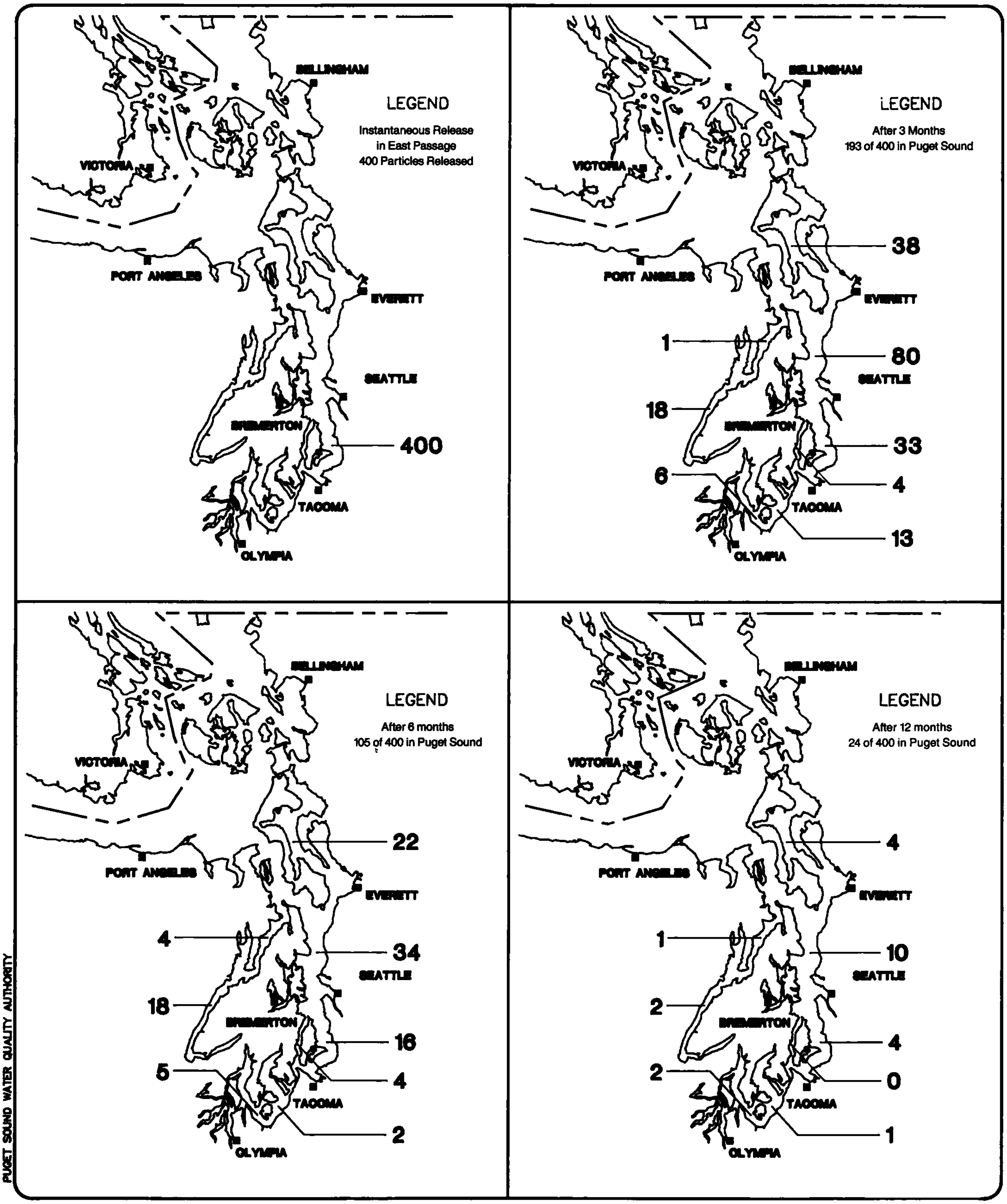
MARINE HABITATS

The factors that differentiate saltwater habitats include temperature, salinity, wave exposure, current speed, depth, availability of nutrients, and the texture, stability, and chemistry of the underlying rock or sediment. Habitats and the organisms associated with them can be grouped into broad categories based on their major differences. The first distinction is between bottom (benthic) habitats and open water (pelagic) habitats that have little or no interaction with the bottom. Benthic habitats are further divided into those that are in shallow and in deep water, and each of those is divided on the basis of bottom texture--hard (rock and gravel) or soft (sand and mud) (Figure 12). Shallow water marine habitats are also classified by the degree to which they are exposed by the rising and falling tides. The stretch of bottom that is covered and uncovered by tides is the intertidal zone. The bottom in the subtidal zone is always submerged.

Open Water

The plants and animals of the open water habitat live independently of the sea bed. Most of the living matter in the open waters of Puget Sound is free--floating plankton: either phytoplankton (plants) or zooplankton (animals). These organisms are usually quite small, ranging from microscopic (single-celled algae) to half an inch (for large zooplankton) in size. Phytoplankton is a major original source of food for the Sound as a whole. Zooplankton feeds on phytoplankton and, in turn, becomes prey for larger animals such as fish.

Plankton organisms reproduce rapidly during the growing season, producing one to dozens of generations per year. Because they are short-lived, their abundance closely follows the seasonal variation in sunlight that drives the



PUGET SOUND WATER QUALITY AUTHORITY

Figure 16

DISPERSION OF THEORETICAL WATER PARCELS IN PUGET SOUND

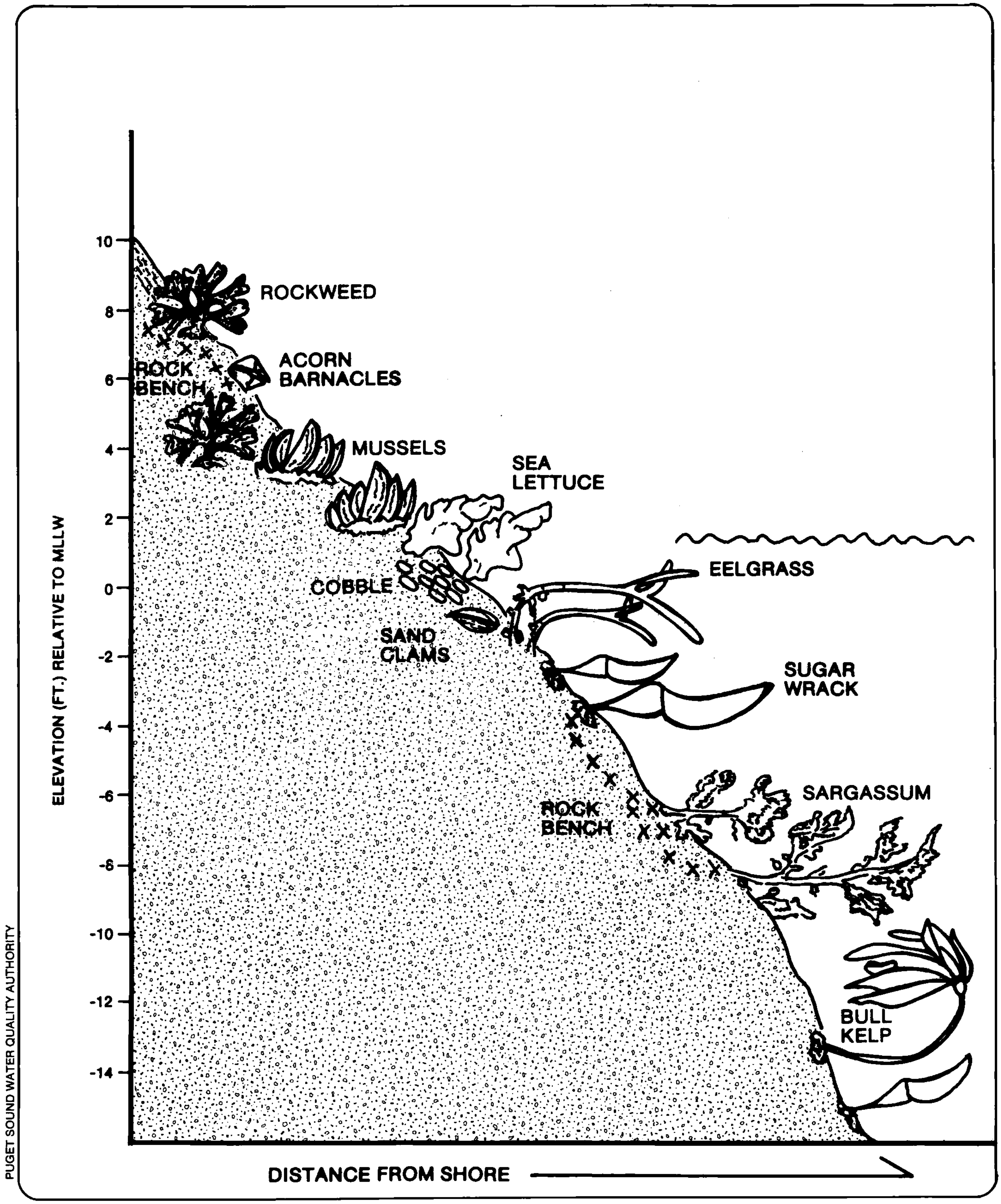


Figure 17

TYPICAL SHORELINE IN THE MAIN BASIN OF PUGET SOUND SHOWING INTERTIDAL HABITATS

growth of plants; most growth occurs between March and September. Phytoplankton growth in the spring is enhanced by stratification of the water which holds the floating plants within a stable surface layer where sunlight is most intense, producing an outburst called a bloom. Thus, the Sound is usually most productive in spring, in phase with the stratification produced by river runoff from melting snow. Strongly mixed areas such as sills are less productive because phytoplankton are mixed below the depth reached by sunlight. Strongly stratified areas lose productivity later in the summer as the plants use up available nutrients. In some bays, such as Budd Inlet and the southern reaches of Hood Canal, chronic stratification, together with limited water exchange, permits decay of organic matter produced by plankton to consume oxygen in subsurface waters. This oxygen deficiency (anoxia) can cause fish kills and offensive odors.

Many bottom-dwelling (benthic) animals spend the first stages of their lives as plankton. At certain times of the year surface waters may be filled with the planktonic larvae of crabs, clams, shrimp, snails, sea urchins, starfish, worms, and other creatures, and with the eggs and larvae of some bottom fish (notably sole). In fact, an estimated 50 percent of all benthic animals have planktonic larval stages. These larvae feed on plankton, and, in turn, are food for fish.

Familiar inhabitants of open water include the baitfish (herring, surf smelt, sand lance) and the salmonids (sockeye, pink, chum, coho, and chinook salmon, steelhead, and cutthroat trout). Many stocks of herring alternate between feeding in Puget Sound and the Strait of Georgia in winter and in the Pacific Ocean in summer. Salmonids are anadromous--that is, adults leave the ocean and enter fresh water to spawn, and juveniles return to saltwater. Most salmon migrate to the Pacific to feed as adults, but some remain as permanent residents in the Sound.

Pelagic fish and zooplankton are prey for sea birds and marine mammals. Pelagic birds (ducks, loons, grebes, auklets, puffins, murres, phalaropes, cormorants, gulls, and terns) consume the smaller and younger fish and some zooplankton. The top predators of the pelagic zone in Puget Sound are the orca ("killer") whales which eat fish, squid, and other mammals. Orcas travel in groups called pods, three of which, comprising about 80 individuals, now inhabit the Sound. Other marine mammals are observed in the Puget Sound basin. Populations of porpoises, sea lions, and harbor seals are present, and there are seasonal visits by fish-eating elephant seals and California sea lions in winter and by plankton-feeding minke whales and bottom-feeding gray whales in summer. During 1986 an unusually large colony of sea lions resided in Puget Sound, consuming hake in the Whidbey Basin and steelhead entering the Lake Washington Ship Canal and the Duwamish River.

Many of the birds and mammals observed in the Sound breed elsewhere, including the gray and minke whales, elephant seals and sea lions, and many of the pelagic birds. Harbor seals and resident Orcas both breed and raise their young in the Sound.

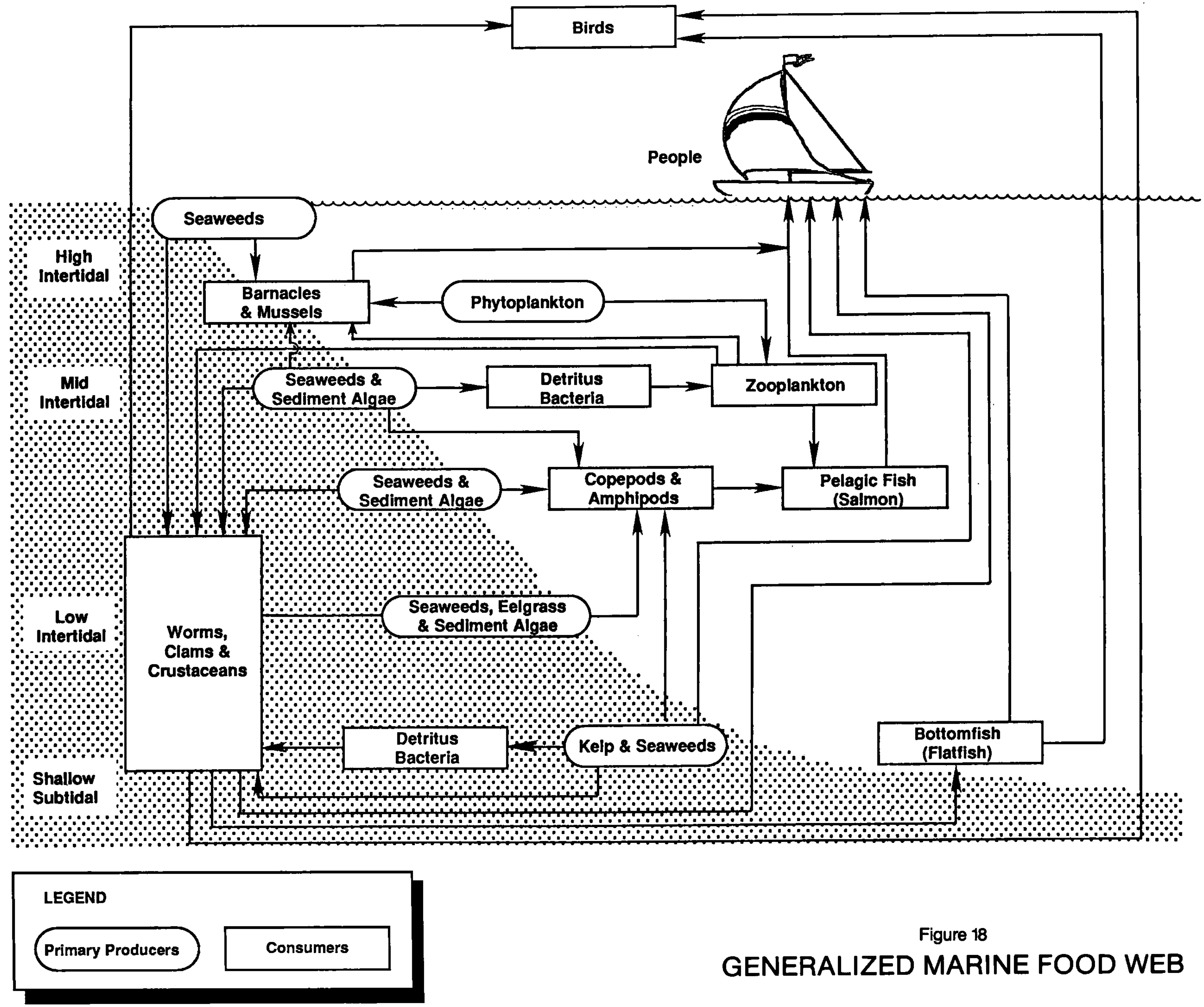


Figure 18

GENERALIZED MARINE FOOD WEB

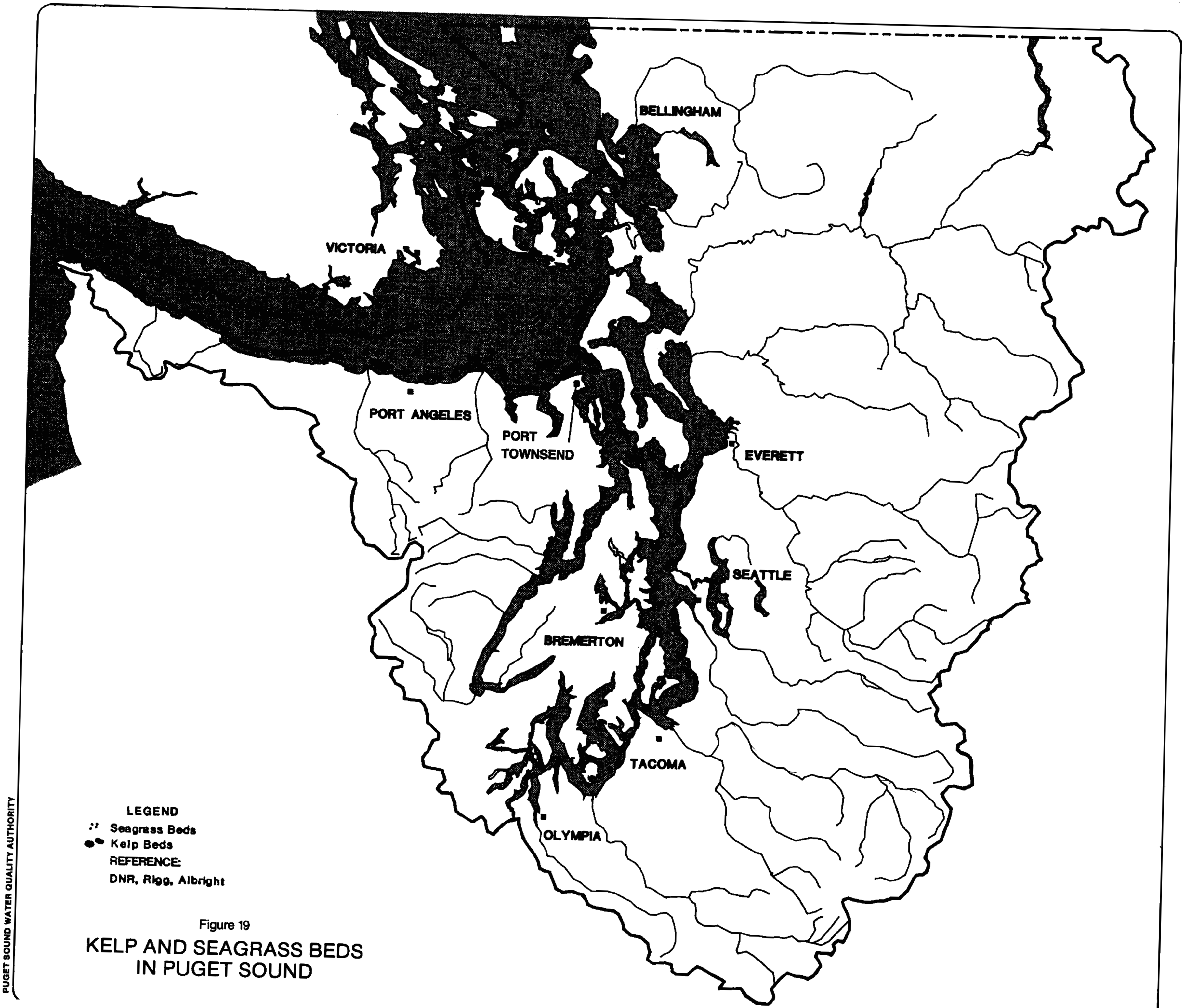


Figure 19

KELP AND SEAGRASS BEDS
IN PUGET SOUND

Rocky Intertidal and Subtidal Habitat

Where the shoreline of Puget Sound is composed of seawalls or outcrops of solid rock (mostly in the northern Sound and San Juan Islands), it supports a biological community that is able to attach to a hard substrate. Most of the plants and animals in this habitat have adaptations either for gripping the rock or for taking refuge from the strong wave action and currents which are usually present.

Two classes of plants are found here. Microscopic benthic algae, relatives of the floating phytoplankton, attach to rocks and form a living coating. Much more visible are the seaweeds, ranging from small red crusts and tufts to leafy green sea lettuce, brown rockweeds, red nori, and giant brown kelp (Figure 19). Seaweeds do not root into the bottom and draw nourishment from it like land plants or eel grass. Instead, they are attached by a holdfast that secures them against currents. Both the benthic microalgae and the seaweeds draw their nutrients from the surrounding water. Both are also limited to growing close enough to the water's surface that light reaches them. Seaweeds and benthic microalgae are more productive than phytoplankton within the shallow areas they cover and may be important sources of organic matter to nearby detrital food webs. In addition, seaweeds are themselves a habitat for certain fish and invertebrate animals. However, they are confined to a narrow strip nearshore and contribute less than phytoplankton to the primary productivity of the Sound as a whole.

The herbivores in this environment use two principal strategies for feeding. Some of them such as snails, chitons, and limpets graze on benthic microalgae by scraping them off the rocks. Others such as barnacles and mussels strain the surrounding water for phytoplankton and detritus which are the major food sources for the community as a whole. Many of these animals have heavy shells to protect them from wave action and from predators such as starfish. Most carnivores in this environment seek different prey: anemones capture zooplankton, small fish, and dislodged snails and mussels; and crabs, shrimps, and sea urchins search the bottom for organic debris. Birds such as gulls, oyster catchers, cormorants, herons, and kingfishers prowl at low tide for any of the herbivores they can capture.

A distinct assemblage of fish is found in rocky habitats. Specialized species including sculpins, clingfish, and gunnels inhabit tide pools. Subtidal rocky areas host a great diversity of sculpins, rockfish, sea perch, greenlings, pricklebacks, and gunnels. These species do not migrate extensively like the pelagic fish but linger in the vicinity of submerged nearshore rocks and reefs. Artificial reefs have been constructed by the state to shelter and create new habitat for these popular types of sport fish. Deeper still in rock hollows lives the largest of the greenlings, the ling cod, a valuable sport and commercial fish.

A related hard-substrate community is found on and around docks and pilings and even on floating debris. This community includes many of the organisms from rocky shores, including some not mentioned earlier: sponges, tunicates, hydroids, bryozoans, and tube worms which colonize driftwood. The larval stages of most of the rocky-shore animals float freely in the plankton and will attach to any hard surface, even to ships, creating a characteristic fouling or settling community. Stationary pilings host anemones and starfish which live

in deeper water, and they attract visiting perch and rockfish. Untreated wood is vulnerable to attack from burrowing organisms including the shipworm (actually a boring clam) and the gribble (an isopod crustacean).

Sandy and Mixed Coarse Sediment Habitat

Habitats characterized by coarse sediment, from pure sand to mixtures of sand, gravel, and cobbles, make up most of the beaches of the Puget Sound basin and are found subtidally in such places as the western shore of Whidbey Island, where there is frequent heavy surf, and on the crests of the sills at Admiralty Inlet and Tacoma Narrows, where tidal currents scour the bottom (Figure 12). They also may be found offshore from rocky reef outcrops. These coarse substrates often are subject to energy from waves and currents that can equal that of many rocky habitats. However, they do not offer as firm a substrate to which organisms can anchor. Thus, to find shelter in these kinds of environments, organisms commonly burrow into the bottom.

The plants that live in the shallow reaches of these environments are benthic microalgae coating rocks and sand grains, and seaweeds that cling to rocks. The dominant herbivores are clams that dig in the sand or hide between rocks (intertidal and subtidal cockles; manila, littleneck, horse, and butter clams; and subtidal geoducks). Some filter-feeding, burrowing worms also may be present. Their principal food is phytoplankton and detritus from the overlying water. Among animals found in this habitat are burrowing harpacticoid copepods, resembling little shrimp, which are an important food source for juvenile salmon.

The intertidal and shallow subtidal zones of mixed sand and cobble beaches support some of the representatives of rocky shores and some of those from quieter muddy shores. This habitat hosts a variety of crustaceans, echinoderms, and molluscs, and both pelagic and bottom fish. Birds present here include murres, puffins, auklets, and cormorants. Oyster catchers choose this type of beach for their breeding sites, along with kingfishers and falcons. Shorebirds such as ducks, geese, sandpipers, and crows are common foragers.

Muddy Intertidal and Subtidal Habitat

The softest and finest-grained bottom habitats in Puget Sound are extremely productive. Muddier areas tend to be those of the weakest water circulation and the most gradual slope and are found mostly at the heads of protected bays and mouths of rivers. The intertidal zones of these habitats, especially at large river mouths, often grade slowly upland into saltwater marshes and are commonly included in discussions of wetland environments. Although intertidal mudflats may not seem like the prettiest shorelines to look at or walk across, they are vital habitats for many highly prized species of fish and birds, and the biological production of the entire Sound depends heavily on these habitats.

The environments that can be placed under this category are fairly heterogeneous. It is not always clear where to draw the distinction between muddy and sandy bottoms, especially in shallow waters and where larger gravel and cobbles are found. Animals found in the transitional environments between sand and mud include sand dollars, sand sole, sculpins, and the giant moon snail. Oysters are found attached to hard surfaces (especially other oyster

shells) atop soft sediments in the intertidal zone. The distribution of culture and spawning grounds of one species of commercial oyster is shown in Figure 20.

Deep water soft-bottom habitats are widespread throughout the Sound at the bottoms of basins or in inlets with sluggish circulation. The food source for these habitats is fallout of detritus from overlying water or organic materials carried down from shallow environments. Characteristic assemblages of clams, worms, starfish, sea cucumbers and urchins, crabs, hydrocorals, and brachiopods inhabit various depths in this domain. Some popular sport fish also dwell here, including flounders and soles. Their flat shapes are an adaptation for living close to the sediment surface, and they feed principally on benthic organisms.

Many muddy habitats support some of the larger burrowing filter feeders such as large clams. Because of the weaker circulation, greater bacterial activity, and greater occurrence of small animals between sediment particles, there is both a much greater demand for oxygen and a smaller supply of it below the sediment surface than in sandy bottoms. Commonly, all the mud below the upper few centimeters is lacking in oxygen (anoxic), is black, and smells of sulfides. Few animals can live in this zone of decay without arranging to pump oxygen-containing water from above. Those that live there have some tolerance to anoxia and circulate water through their burrows to assure a steady supply of oxygen.

The soft bottom community includes some small worms that feed from overlying waters; microscopic animals that live on sediment grains and consume bacterial and algal coatings; tiny crustaceans that live between sediment grains; and larger "deposit feeders" including certain worms and clams and ghost shrimp.

Eelgrass

Shallow subtidal soft-bottom communities are often characterized by the presence of eelgrass, a dominant plant species and one of the most important in Puget Sound (Figure 19). Unlike the seaweeds, it is not a type of algae but instead a flowering perennial that roots in the soft submarine soil just at the low tide line and draws nutrients from the rich accumulation of organic matter in the mud. The chemistry of the mud, in fact, is critical to the productivity of these systems. The finest detritus--from eelgrass, other plants and animals, and from rivers and waters of the Sound--settles in these quiet waters. Organic matter also coats tiny grains of silt and sand. Bacteria break down this material and regenerate its nutrients to produce the equivalent of the finest garden compost. In addition, the sediment surface throughout the intertidal and shallow subtidal zones is carpeted with benthic microalgae that, together with fallout from phytoplankton growth in the overlying water, further enrich the organic content of the mud.

In deeper water, eelgrass provides food, substrate, and shelter for a great diversity of organisms. Most animals do not consume eelgrass directly, but eat either its decayed detritus or the microalgae, seaweeds, organic coatings, bacteria, and microfauna that colonize its surfaces. The herbivores and omnivores that feed directly off eelgrass surfaces include flatworms, snails, and small crustaceans. These, in turn, support a menagerie of carnivores such as nudibranch snails, jellyfish, and certain crabs, starfish, and sea cucumbers.

Muddy shorelines including eelgrass beds perform an important role in supporting the larval and juvenile stages of many types of commercial and sport fish. Just after they enter saltwater, juvenile salmon feed extensively on small worms and crustaceans living on mud. Surf smelt spawn on protected beaches, and herring deposit their eggs predominantly on eelgrass blades (Figure 19). The major herring spawning area in the Puget Sound basin is an extensive eelgrass bed in the southeastern Strait of Georgia. Large numbers of resident fish also live within the eelgrass habitat including tube-snouts, sticklebacks, pipefish, and sculpins.

A more visible role of muddy shallows is their support of resident and migratory bird populations. The distribution of shorebirds (Figure 21) is related to that of eelgrass. Some birds, such as the black brant, consume eelgrass directly. Many more shorebirds (herons, swans, geese, ducks, plovers, sandpipers, phalaropes, gulls, and terns) walk the mudflats in search of small worms, crustaceans, and fish. Open water birds such as loons, grebes, alcids, and diving ducks enter this nearshore environment seeking juvenile herring and salmon. Wetland habitats including the Nisqually and Skagit Flats, Padilla Bay, and Dungeness Spit are bird feeding areas of importance to the entire Pacific coast.

Sheltered bays, especially in the southern Sound and the San Juan Islands, are the habitat of an additional Puget Sound mammal, the harbor seal. Harbor seals feed below the surface on fish such as herring, flatfish, sculpins, and hake. They rest or "haul out" on secluded beaches, pilings, docks, and barges (Figure 22).

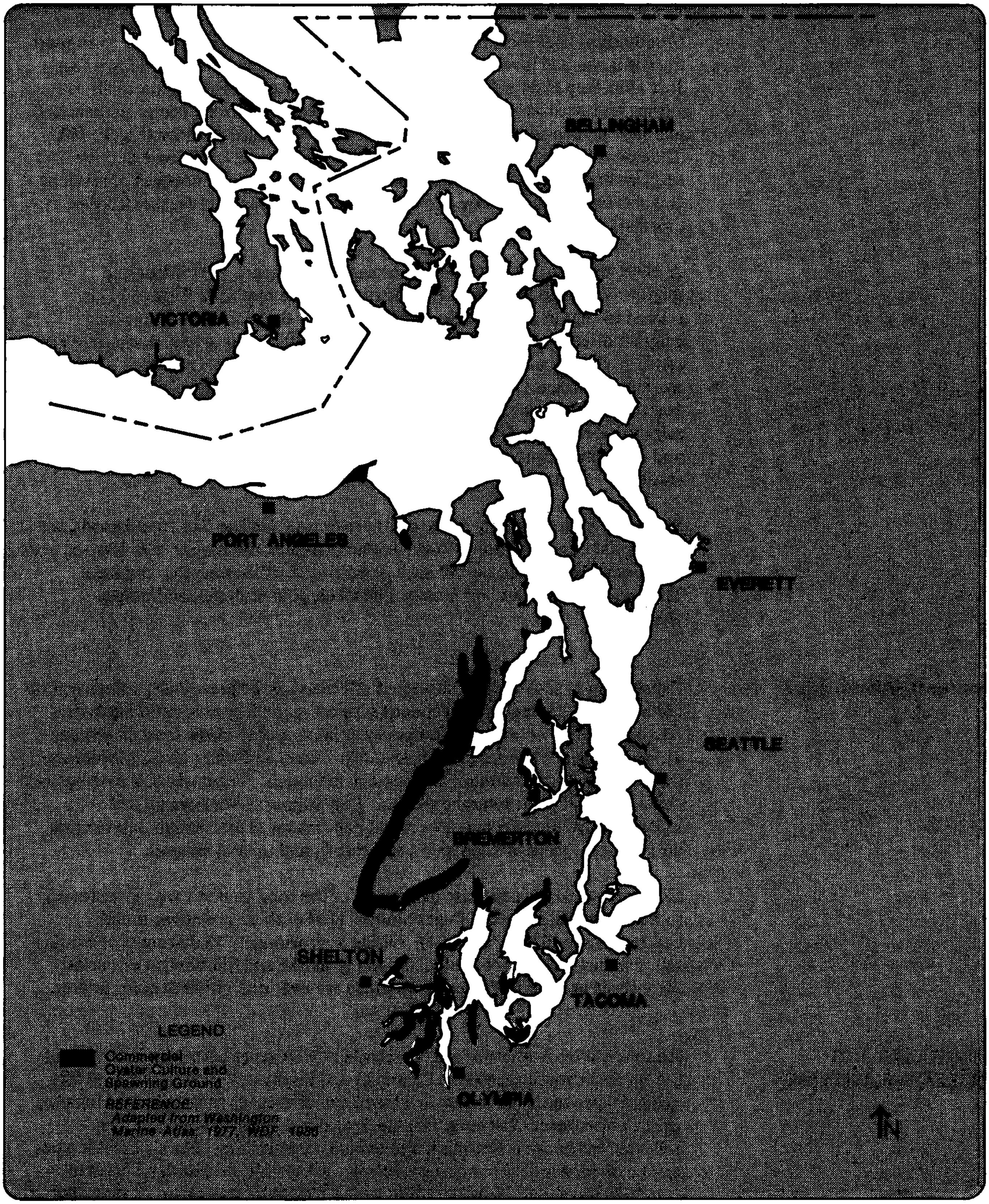
Estuarine Wetland Habitat

Estuarine wetlands include vegetated salt marshes, eelgrass beds, and unvegetated mudflats. Unvegetated wetlands support secondary production activities (i.e., the feeding on microorganisms by animals higher in the food chain) and are an important habitat for fish, shellfish, marsh and water birds, shorebirds, waterfowl, and coastal marine or aquatic mammals. Vegetated salt marshes are characterized by salt tolerant grasses. They support both primary and secondary productivity and are critical habitats for crabs, shrimp, marine fish, birds (ducks, geese, herons, gulls, and terns), and upland animals.

Estuarine wetlands comprise 62 percent of the total wetland area inventoried to date near the shores of Puget Sound. Half of these are unvegetated beaches or mudflats (Figure 24). Of the approximately 13,000 acres of existing salt marshes, 61 percent are located in the Skagit and Snohomish estuaries. Sixty-three percent of estuarine wetlands are over one hundred acres in area.

FRESHWATER AND TERRESTRIAL HABITATS

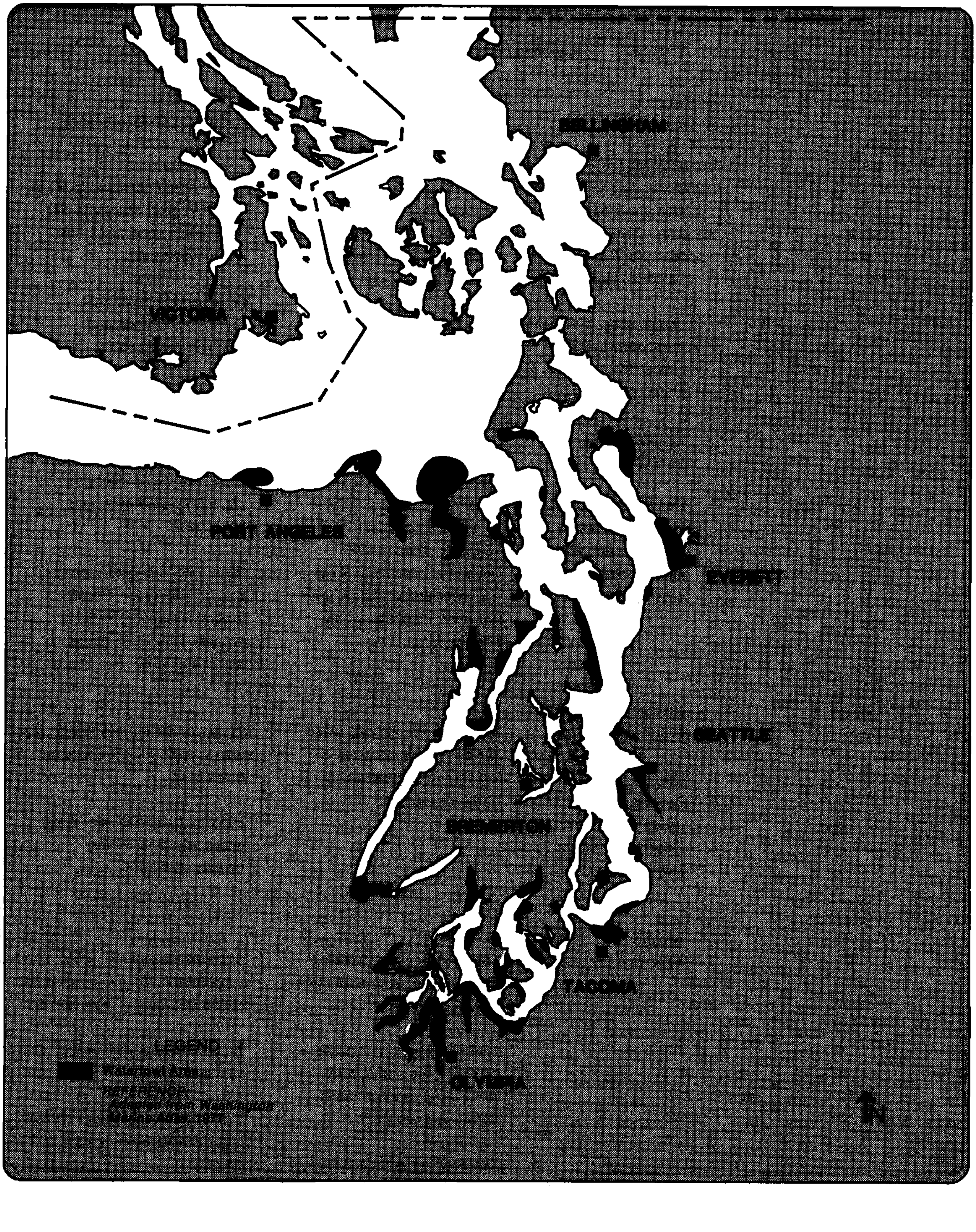
Representative freshwater and terrestrial habitat types occurring in the Puget Sound basin are illustrated in Figure 23 and briefly described in Table 2. Six habitat types can be distinguished based on differences in the physical features of the environment (altitude, climate, hydrology, soils) that are, in turn, reflected in characteristic plant and animal communities. The six habitat types can be divided into two major groupings: lake, river, and wetland habitats comprise the aquatic habitat group; alpine highlands, evergreen forests, and deciduous forests comprise the terrestrial habitat group.



PUGET SOUND WATER QUALITY AUTHORITY

Figure 20

DISTRIBUTION OF COMMERCIAL PACIFIC OYSTER CULTURE AND SPAWNING GROUNDS



PUGET SOUND WATER QUALITY AUTHORITY

Figure 21

MAJOR WATERFOWL HABITATS
IN PUGET SOUND

TABLE 2: COMMON UPLAND HABITAT TYPES IN THE PUGET SOUND BASIN

HABITAT TYPE	TYPICAL PLANT COMMUNITIES	TYPICAL ANIMAL COMMUNITIES
ALPINE HIGHLANDS Generally non-forested zone above 5,000 feet in the Olympic Mountains, Mt. Rainier and Cascade range. Fragile ecosystem highly susceptible to disturbance. Many include ice fields and glaciers.	This habitat type occurs above the timberline and includes such plants as lupine, Indian paint brush, black cowberry, and mountain heath.	Mammals include hoary marmot, mountain goat, Roosevelt elk, black-tailed deer, black bear, and meadow vole. Birds include water pipit, Clark's nutcracker, and rufous hummingbird.
EVERGREEN FORESTS Dominant forest habitat in the Puget Sound drainage area. Heavily affected by logging activities.	Douglas fir, noble fir, western hemlock, and cedar in lower elevations. Alpine fir, silver fir, mountain hemlock, and lodgepole pine at higher elevations. Disturbed areas due to logging or fire include red alder, huckleberry, and bracken fern.	Mammals include chipmunk, deer mouse, coyote, snowshoe hare, elk, black-tailed deer, and black bear. Birds include western tanager, evening grossbeak, Clark's nutcracker, raven, Stellar's jay, and various species of hawks and owls.
BROADLEAF (DECIDUOUS) FORESTS May be cleared for farming, firewood, or urban development. Generally occur at low elevations.	Alder, vine maple, oak, aspen, and ash. Typically occur on wet soils or in areas disturbed by fire or logging.	Mammals include chipmunk, deer mice, coyote, rabbit, elk, and black bear. Birds include sparrows, chickadees, starlings, robins, finches, owls, and hawks.
LAKES Most glacially formed.	Microscopic algae including green, diatom, and--sometimes--bluegreen species. Shallow water rooted plants including pond lilies, pond weed, water weed, coontail, milfoil, and cattails. Shoreline trees include alder, willow, cottonwood, and ash.	Microscopic animals called zooplankton. Important species called Daphnia or "water fleas." Aquatic insects such as mayflies and midges. Reptiles and amphibians such as frogs, salamanders, snakes, and turtles. Fish of various species including rainbow trout, salmon,

TABLE 2: COMMON UPLAND HABITAT TYPES IN THE PUGET SOUND BASIN (continued, page 2)

HABITAT TYPE	TYPICAL PLANT COMMUNITIES	TYPICAL ANIMAL COMMUNITIES
LAKES (continued)		yellow perch, bass, brown bullhead, and suckers are common. Mammals such as beaver, muskrat, mink, otter, and raccoon. Waterfowl such as Canadian geese, mallard, and coots.
RIVERS Most common recipients of point source pollutant discharges asciated with activities inland from Puget Sound.	Microscopic algae including green, diatom and bluegreen species. Macroscopic filamentous algae like Chladophora (attached to rocks). Shallow water rooted plants including pond lilies, pond weed, water weed, milfoil, and cattail. Normally occurring in areas of slow water movement. Shoreline trees include alder, willow, cottonwood, and ash.	Microscopic animals called zooplankton including Daphnia or "water fleas". Aquatic insects such as midges mayflies, stoneflies, and caddisflies. Various fish species including salmon, steelhead, and rainbow trout. Reptiles and amphibians such as frogs, salamanders, snakes, and turtles. Mammals such as beaver, muskrat, mink, otter, and raccoon. Waterfowl such as Canadian geese, mallard, and coots.
FRESH WATER WETLANDS Lowland areas usually adjacent to rivers and lakes with wet, organic soils and characteristic plant species.	Trees include alder, willow, aspen, ash, cottonwood, cedar, and hard hack. Other plants include sedges, rushes, cattails, pond lilies, salmonberry, and salal.	Microscopic animals called zooplankton. Important species called Daphnia or "water fleas." Aquatic insects such as mayflies and midges. Reptiles and amphibians such as frogs, salamanders, snakes, and turtles. Fish of various species including rainbow trout, salmon, yellow perch, bass, brown bullhead and suckers. Mammals such as bear, muskrat, mink, otter and raccoon. Waterfowl such as Canadian geese, mallard, and coots.

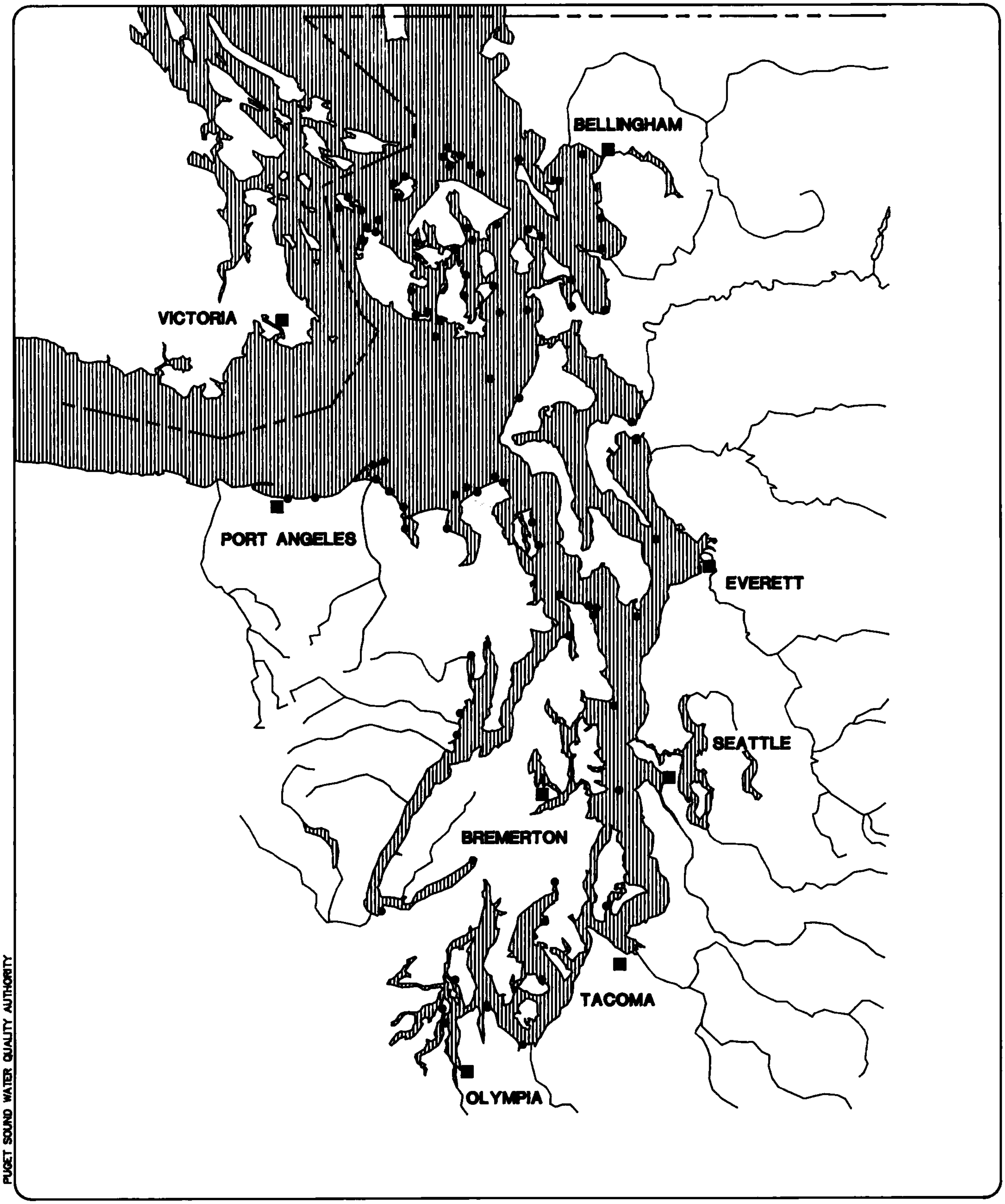


Figure 22

SEAL AND SEA LION HAULOUTS
IN PUGET SOUND

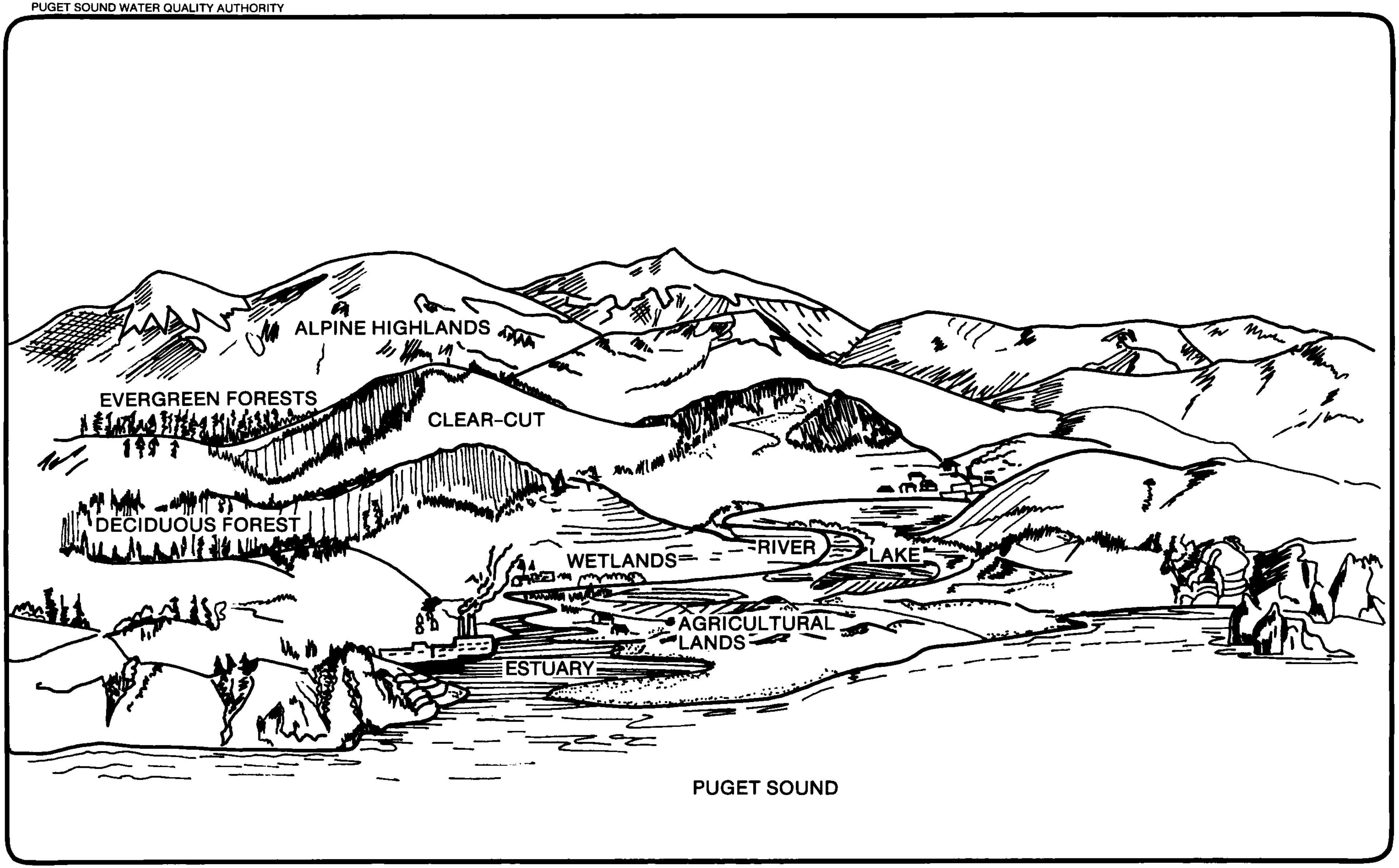


Figure 23

REPRESENTATIVE TERRESTRIAL HABITATS IN THE PUGET SOUND WATER QUALITY PLANNING AREA

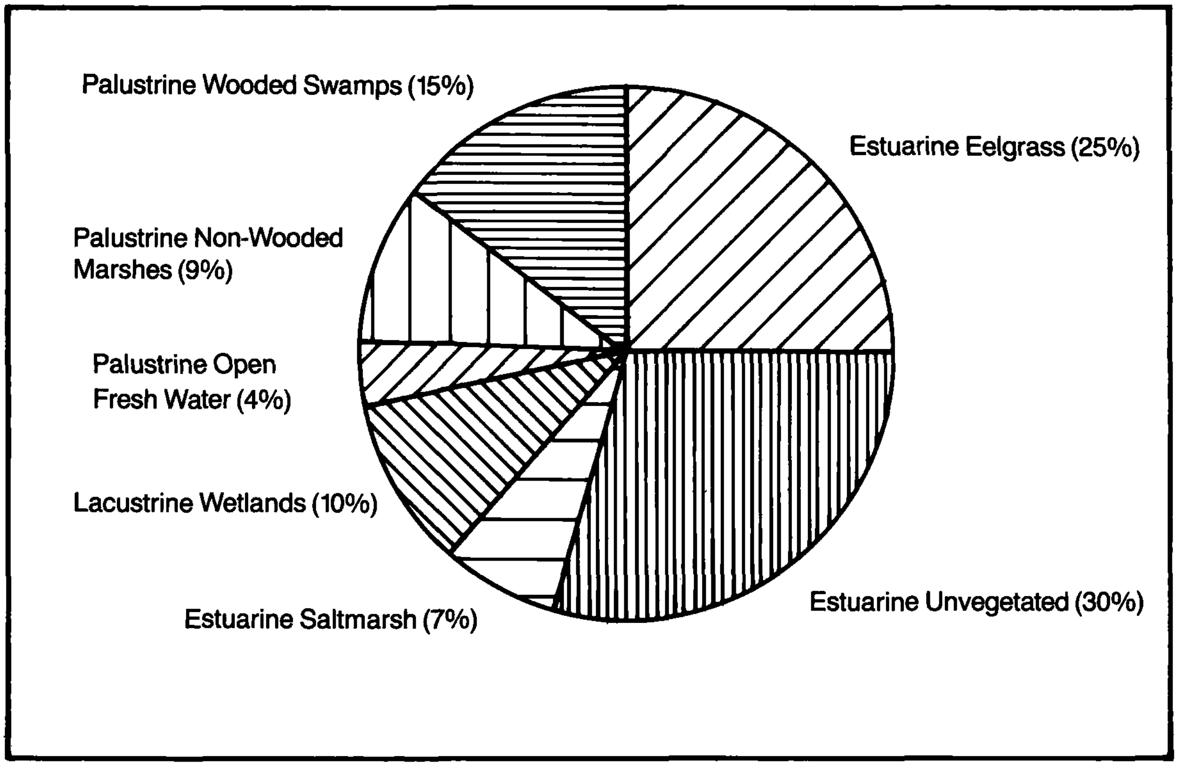


Figure 24

RELATIVE ACREAGE OF DIFFERENT WETLAND TYPES IN THE PUGET SOUND WATER QUALITY PLANNING AREA

Major human activities such as timber harvesting, agriculture, and urban land development that occur in terrestrial habitats can produce changes in hydrology and water quality and affect aquatic habitats. Aquatic habitats can also be affected directly by activities such as filling of wetlands, damming and channelization of rivers, diking, dredge spoil disposal, and shipping and boating. Since wetlands, lakes, streams, and rivers ultimately connect with Puget Sound, any effects from water quality on these aquatic habitats have the potential to result in similar effects on Puget Sound itself.

Freshwater Wetland Habitats

Freshwater wetlands are the transition zone between aquatic and terrestrial environments. Saturation of the soil with water is the dominant characteristic of this habitat, and determines the soil development and resident plant species. The soils are saturated or inundated often and long enough that only vegetation adapted for life in wet soils can survive. Freshwater wetlands include open water, marshes, bogs, swamps, and rocky river reaches.

Freshwater wetlands can be separated into two categories:

Lacustrine - Lakes and wetlands that are in close proximity to lakes.

Palustrine - All persistent wetlands that are adjacent to streams, bays, and estuaries or created by springs, seeps, or surface runoff. They are typically called marshes, bogs, swamps, and ponds. Most are vegetated with submergent or emergent woody or non-woody plants.

Lacustrine wetlands are used by waterfowl, shorebirds, marsh and water birds, fish, and a variety of predatory mammals such as raccoons (Table 3). In heavily forested areas wetlands are important to deer and bear for water and food. Lakes in close proximity to the Sound are frequently used as escape cover for waterfowl during heavy storms. Lacustrine wetlands make up 10 percent of the wetland area inventoried around Puget Sound (Figure 24). Of these, 45 percent are located in Skagit County, 20 percent in Pierce County, and 10 percent each in King and Kitsap Counties. Nine lakes over one hundred acres in size comprise 48 percent of the total area, while 106 lakes between 10 to one hundred acres in size comprise another 51 percent.

Palustrine wetlands are the most diverse and scattered group of wetlands adjacent to Puget Sound. They are also the least adequately inventoried. Palustrine marshes are found in areas with relatively large amounts of flat land at low elevations. They include small ponds, freshwater cattail marshes, wet pastures, backwater areas along streams, shrub swamps, hillside seeps, and bogs. A majority (over 80 percent) are vegetated. Most are less than 10 acres in size, but the few wetlands between 10 and one hundred acres in size have a greater total surface area than all of the smaller wetlands combined.

There are four types of palustrine wetlands (Figure 24): open fresh water, non-wooded marshes, wooded swamps, and unvegetated. Unvegetated palustrine wetlands constitute much less than one percent of the total and are not represented in Figure 24. Most open water marshes have some emergent or floating vegetation. Non-wooded wetlands include cattail and bullrush marshes,

TABLE 3: FISH AND WILDLIFE USES OF DIFFERENT WETLAND TYPES

S - Spring
S - Summer
F - Fall
W - Winter

◆ - Areas are used but are not high priority sites
● - Areas receive heavy use, are important during one phase of life cycle
■ - Areas are critical to the survival of one or more species in the group

Fish and Wildlife	Un-Vegetated Estuarine				Saltmarshes				Lacustrine				Open Water Palustrine				Non-Woody Palustrine				Woody Palustrine			
	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W	S	S	F	W
Shellfish																								
Non-mobile (oyster, clams)	■	■	■	■																				
Mobile (crabs, shrimp)	■	■	■	■	■	■	◆																	
Fish																								
Salmonids (salmon, trout)																								
Migratory	■	■	■	◆	●	●	●	●					◆	◆	◆									
Resident									●	●	●	●	◆	◆	◆	◆	◆	◆	◆	◆				
Marine fish (flatfish, spiny)	■	■	■	■	■	■	◆	◆																
Freshwater (bass, bluegill)									■	■	■	■	●	●	●	●	◆	◆	◆	◆				
Reptiles and amphibians						◆	◆		■	■	●	●	■	■	●	●	◆	◆	◆	◆	■	◆	◆	◆
Birds																								
Water birds (loons, grebes)																								
Waterfowl (ducks, geese, swan)	◆	◆	◆	◆	●	●	●	●	●	●	●	●	■	■	■	■	■	■	■	■	■			
Raptors (hawks, eagles, owls)					◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	●	●	◆	◆	●	●	◆	◆	◆	◆
Marsh birds (herons, egrets)	●	●	●	●	●	●	●	●	●	●	◆	◆	■	■	■	■	■	■	■	■	■	■	◆	◆
Wading birds (cranes, rails)									●	●	◆	◆	◆	◆	◆	◆	■	■	■	■	■	●	◆	◆
Shorebirds (plovers, sandpipers)	■	●	■	■		●	●		◆	◆	◆	◆	◆	◆	◆	◆	■	■	◆	◆				
Gulls and terns	●	●	●	●	●	●	●	●	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆				
Marine birds (auklets, murres)	◆		◆	◆																				
Passerine (jays, warblers, wrens)		◆				●			●	●	●	●		●	●				●	●	●	●	●	●
Upland game (pheasants, grouse)																		●	●			●	●	
Mammals																								
Marine (seals, sea lions)	◆	◆	◆	◆																				
Predators (raccoon, coyote)	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Freshwater aquatic (otter, beaver)									■	■	■	●	■	■	■	■	■	■	■	■				
Deer family (deer, elk)	◆	◆	◆	◆					◆	◆	◆	◆					◆	◆	◆	◆	◆	◆	◆	◆
Bear	◆	◆	◆	◆	●	◆	◆	●	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆

shallow sedge/rush/grass marshes, and wet meadows. Wooded wetlands (swamps) usually are a mix of shrubs such as salmonberry, wild spirea (hard-hack), and willow and trees such as alder, cottonwood, willow, and spruce. Wetter swamp pockets frequently have stands of skunk cabbage, water parsley, or horsetail. Wooded wetlands are frequently found in seep areas that partially or completely dry out in the summer. Most have peat or muck soils.

Vegetated wetlands are richly productive environments that sustain both plants and animals. Dense vegetation slows water movement, causing settling of suspended solids and their associated nutrients and further enriching the wetland plants. Some plants and the bacteria that live on them absorb or consume elements or compounds that cannot be used by other plants or animals in that form. They then convert them to usable forms through digestion or other metabolic functions. These usable forms are released either in waste products or during decay of the plants, during their dormant season, to become a usable part of the organic food base. Integrated wetland complexes of ponds, marshes, and woods offer the isolation necessary for nesting and brood rearing. Beaver ponds are a prime example of these types of systems.

Open ponds and non-wooded marshes are excellent wildlife habitats for a variety of waterfowl, marsh birds, and mammals in the Puget Sound area and in some instances are, like estuarine wetlands, rearing and feeding areas for certain species of juvenile salmon. Grass pasture areas near ponds or streams are nesting and rearing areas for waterfowl. Wooded swamps near an open water area or permanent stream can provide nesting and cover for marsh birds such as herons and wading birds such as rails. These areas also support passerine birds such as jays, warblers, and wrens.

Wetlands perform a number of valuable hydrologic functions. They slow runoff flows, reducing erosion and increasing the amount of sedimentation. They absorb pulses of floodwater and discharge them more gradually. They are entry points for recharge of groundwater. They also perform the biological functions of providing food and habitat for important species of animals including birds and mammals (Table 3).

Prior to alteration by intensive human development, Puget Sound was unquestionably one of the environmental wonders of the world. The degree to which Puget Sound has been affected by the uses and demands made of it is determined by the natural characteristics described in this chapter, and by the human development of its basin, the subject of the next chapter.

II. Human Development of the Puget Sound Basin

INTRODUCTION

Ten thousand years after the end of the last Ice Age the Puget Sound basin was home to several thousand people. Today the population of the basin is around 2.9 million. The human ability to alter the natural environment makes this large population possible, but many of these alterations damage the quality of the environment. Some of the activities that affect water quality such as dumping of domestic and industrial waste are obvious and intentional; others are less obvious and often unintentional. Human activities tend to damage the environment. The larger the population, the more human activities there are. Over the years, as the regional economy changes, as lifestyles change, and as we learn about and respond to the environmental consequences of human activities, the amount and type of damage created by those activities is reduced. A consideration of the human habitation and economic development of the Puget Sound basin is fundamental to understanding the present and likely future water quality of the Sound. The human uses of the Sound also define its importance to us and to our economy.

Certain industries are considered most important in determining patterns of economic, population, and land use development. Regions have an economic base, a set of industries that are basic to the regional economy. The products of these basic industries are traded for commodities, products, and services that other regions can produce more efficiently. These basic industries in turn support other local businesses such as trade and personal services. Thus, the basic industries are those that generate wealth in an area and create economic growth. The basic sector of the Puget Sound economy began as natural resource industries--timber, mining, fishing, agriculture, and associated processing and manufacturing activities--and transportation, especially shipping. This pattern evolved over the decades to include heavy manufacturing, and today service industries are increasingly important.

This chapter reviews the history of population and economic growth in the Puget Sound region, focusing on changes in the key economic activities that supported development. The histories of these activities determine the magnitude and distribution of their effects on Puget Sound. The connections between human settlement and water quality are dynamic, changing as settlement patterns change, as the regional economic base shifts, and as technology changes.

HISTORY OF DEVELOPMENT IN THE PUGET SOUND WATER QUALITY BASIN

The history of the human development of Puget Sound and lands surrounding it may be divided into several periods. Useful milestones for dividing the course of history include the habitation by Native Americans following the Ice Age, settlement in the area by non-Indians, the coming of the transcontinental

railroads during the 1880s, the Great Depression of the 1930s, the postwar aerospace boom years of the 1950s and 1960s, and the current time period. For a glimpse of the future of the region, we look to the year 2000. (A timeline for the Puget Sound area appears at the end of this chapter.)

Figures 25, 26, and 27 shows population growth in Washington State and the Puget Sound region between 1860 and 1985 and projected growth to the year 2000.

BEFORE 1845: THE NATIVE AMERICAN PERIOD

The last time glacial ice melted away in this area was 10,000 to 20,000 years ago. Humans probably have lived in this region since that time. Indian tribes that reached Alaska, probably from Asia over the Bering Sea land bridge during an Ice Age, filtered into the newly thawed Puget Sound basin. They were the first known human inhabitants of the region.

The Native Americans enjoyed abundant fish and shellfish resources, vast forests, and a temperate maritime climate that was hospitable to human settlement. Local native tribes were part of the Coast Salish people who lived in the area between Powell River, British Columbia, and the Chehalis River on the Washington coast. The native population of the early 1800s has been estimated at several thousand in the central Puget Sound area alone. The Puget Sound tribes were primarily a fishing culture. They harvested salmon, halibut, cod, and other fish, shellfish gathered from the vast tideflats and rocky beaches, and berries and other edible plants as well as upland game of all kinds. Trade was conducted among tribes by water and overland. Thus, early development in the Puget Sound region depended upon harvestable resources and transportation.

In May of 1792, the British sea captain, George Vancouver, and his crew were the first Europeans to explore Puget Sound, naming its islands and mountain peaks after the crew. Puget Sound was named for Peter Puget, a young second lieutenant on board the Discovery. Vancouver extolled the virtues of the region in his journal:

> The serenity of the climate, the innumerable pleasing landscapes, and the abundant fertility that unassisted nature puts forth requires only to be enriched by the industry of man, with villages, mansions, cottages, and other buildings, to render it the most lovely country that can be imagined.

Later, the Puget Sound area was used by fur traders who came north from the Willamette Valley in Oregon. The first trading post on Puget Sound was established in 1833 by the Hudson's Bay Company at Fort Nisqually.

1845 TO 1880: NON-INDIAN SETTLEMENT

The first permanent non-Indian settlement was established at Tumwater in 1845. Although trading ships had visited the Puget Sound region earlier, the first real impetus to growth in the region came in December 1851 when the ship Leonesa called from San Francisco seeking logs for the Gold Rush construction boom in California. In 1852 and 1853, a series of mill towns were

established along the shores of Puget Sound, and by 1853 steam sawmills were operating in Seattle, Port Gamble, Port Ludlow, Appletree Cove, and Alki. Timber products and shipping formed the nucleus of the early industrial economy.

Agriculture and fishery production began at the same time as the timber industry, driven by the high cost of imported food. Clearing of land with the best soils--the flood-prone cedar-swamp river valleys east of the Sound--began during this period. Fisheries resources were exported from the time of earliest non-Indian settlement, first in salt-brine, and later in tin cans.

In these years, Puget Sound was the major link between communities. Travel was almost exclusively by water; an extensive marine transportation system known as the Mosquito Fleet carried people, cargo, and mail between ports. A trading system developed to import and distribute goods not grown or manufactured locally. Tacoma and Seattle vied to be the center of this trading system.

Unlike much of the early non-Indian settlement of the United States east of the Rockies, which was in dispersed farmsteads, non-Indian settlement in the Puget Sound region from the outset was mostly urban. The early mill towns had concentrated work forces, and loggers travelled to the woods from camps or towns. Agriculture bordered mill towns, providing food primarily for local consumption. The land use pattern of the Puget Sound region in this earliest era consisted of small settlements on Puget Sound, a shoreline largely stripped of trees, and some modest lowland agricultural areas near mill towns.

1880 TO 1940: THE BIG BOOM

Resource-oriented industry and transportation propelled the growth of the Puget Sound economy from the arrival of the transcontinental railroads until the Great Depression. Massive increases in timber harvests, non-Indian fish harvests, and agricultural output took place. In addition, the region became the key trading location for much of the Pacific Northwest and Alaska.

In 1883, the Northern Pacific Railroad reached the shores of Puget Sound, and the region became connected by overland travel to the rest of the nation. This connection led to a boom in the regional economy. With the arrivals of the Great Northern Railroad in 1893 and the Milwaukee Railroad in 1906, the region quickly moved out of isolation.

The region's growth was aided when Seattle become the primary outfitting stop for eager prospectors bound for the 1897 Klondike Gold Rush. Trade with the Orient also boosted the local economy. Shipbuilding became important during this time. The Port Blakely mill was the largest single port of call for lumber ships. In 1891 Congress appropriated funds for construction of the Navy drydock at Bremerton, and the Puget Sound Naval Station was dedicated 10 years later.

Economic expansion around Puget Sound went hand-in-hand with a population explosion around the turn of the century. Seattle grew from 3,500 to 40,000 and Tacoma from 1,100 to 36,000 during the 1880s. The new population was concentrated in the larger harbors of Puget Sound's eastern shoreline and

along the tributary rivers (Figure 25). For comparison, Figure 26 shows the population distribution in central Puget Sound in 1980.

Bremerton, the home of the new Navy yard, and Anacortes, the lumber port and railhead of Skagit County, became important during the 1890s, and Tacoma, Everett, and Bellingham also grew rapidly. Farm settlements expanded in the fertile valleys of the Nooksack, Skagit, Snohomish, Green, and Puyallup Rivers, and logging camps moved inland to the higher valleys. Small communities sprouted near the coal fields in the foothills of central King and Pierce Counties. Seattle tripled its population to 237,000 between 1900 and 1910 and surpassed Portland as the largest city in the Pacific Northwest. The region's total 1889 population of 183,000 was more than seven times the 1880 population of 25,000 and grew further to over 600,000 by 1910.

A tremendous expansion in the forest products industry fueled development of the Puget Sound region during this period. Lumber production increased from the 1880 level of 160 million board feet to 1.4 billion board feet by 1900 and to 7.3 billion by 1929. Almost 40 percent of the value of industrial output was estimated to originate in the lumber industry in the 1900 census.

Logging technology underwent major changes during this time period. The introduction of railroads, trucks, steam and gasoline-powered yarding devices, and chainsaws gradually expanded the area that could be logged economically, and mill towns along the shoreline of the Sound gradually waned in significance. Foothill mill towns such as Snoqualmie, White River, and Darrington became the new focus of the Puget Sound forest products industry. At the same time, the industry diversified to include pulp and paper manufacture and plywood production.

Agriculture expanded dramatically, from approximately 100,000 improved acres in 1880 to 227,000 improved acres in 1900 and 554,000 improved acres in 1930. In this early era, more improved farmland was used for growing crops than for pasture.

During this period the non-Indian salmon fishery in Puget Sound boomed as well. Most fish were caught in weirs, set nets, and other impoundments, practices that were not effectively managed to protect fish stocks. Precipitous declines in salmon harvests, due in part to overfishing, occurred in the 1920s. Spawning habitats were rapidly altered during this era and attempts to correct for this included the establishment of hatcheries.

The Puget Sound economy began to diversify during this period. Local firms began producing machinery to support the timber, agriculture, and fishery industries, and these products were sold to other parts of the United States and around the world. A copper smelter was established at Ruston near Tacoma, and shipbuilding prospered.

The period from 1910 to 1940 was one of slower growth for the Puget Sound region, as resource-based industries matured, peaked, and began to decline and as the shift to manufacturing and services began. The region's economy suffered a strong decline during the national depression in the 1930s, and

markets for lumber, coal, and other regional products fell. Coal mining centers and logging settlements began to decline.

The period between 1910 and 1940 did see rapid expansion in transportation and its supporting industries in the Puget Sound region. Port facilities were approved in Tacoma in 1910, and Washington State's first public port was created in Seattle one year later. These ports became extremely busy during World War I, by the end of which they were second only to New York in cargo volume. A wartime shipbuilding boom was intense but short-lived. By the end of World War I, automobiles began to be common, and a network of roads and highways connected Puget Sound cities and towns, tying them with other parts of the state and the nation. As a result, needs for water transportation changed dramatically. By the 1920s, steamers were converted to automobile ferries, and the number of routes was drastically reduced. The first Boeing airplanes were built in Seattle in 1916, and the company began its rise to prominence in the aerospace industry in the 1920s.

Population growth continued in urban areas and in agricultural valleys. Most significant was early suburban growth around the larger cities. Seattle expanded to the north and south, and Tacoma grew to the south. Port Angeles and Shelton thrived due primarily to the development of the pulp industry.

An estimate of the pattern of employment in the Puget Sound regional economy derived from 1930 census data is presented in Figure 28. Manufactured goods and resource products supported 75 percent of the export-related employment and probably also supported much of the employment in transportation and trade.

1940 TO 1970: TRANSITION TO THE MODERN ECONOMY

After the Great Depression of the 1930s, the Puget Sound region again had a period of major expansion and development. During World War II, new industries entered the economic base as major employers--aircraft construction, shipbuilding, and machinery manufacturers. After the post-war recovery and the Korean War, international trade began to develop in new ways. For the first time in this region unprocessed logs were exported, while international trade in manufactured commodities with Far Eastern ports began to flourish.

The relative importance of resource-oriented industries to the regional economy declined after World War II, but employment in key sectors such as forest products remained high. Lumber production in the 12-county Puget Sound region declined from 5.79 billion board feet in 1926 to 2.05 billion in 1950. In general, the economic base of the Puget Sound region diversified as shown in Figure 28. Employment in manufacturing of aerospace and other transportation equipment expanded dramatically during this period. Aerospace became the state's major industry, Boeing plants were built in Renton and Everett, and the Seattle/Tacoma International Airport was developed. The Boeing Company led the expansion in employment in the Puget Sound region, rising to a peak of 105,000 employees in 1969 from a level of about 50,000 during most of the post-war era.

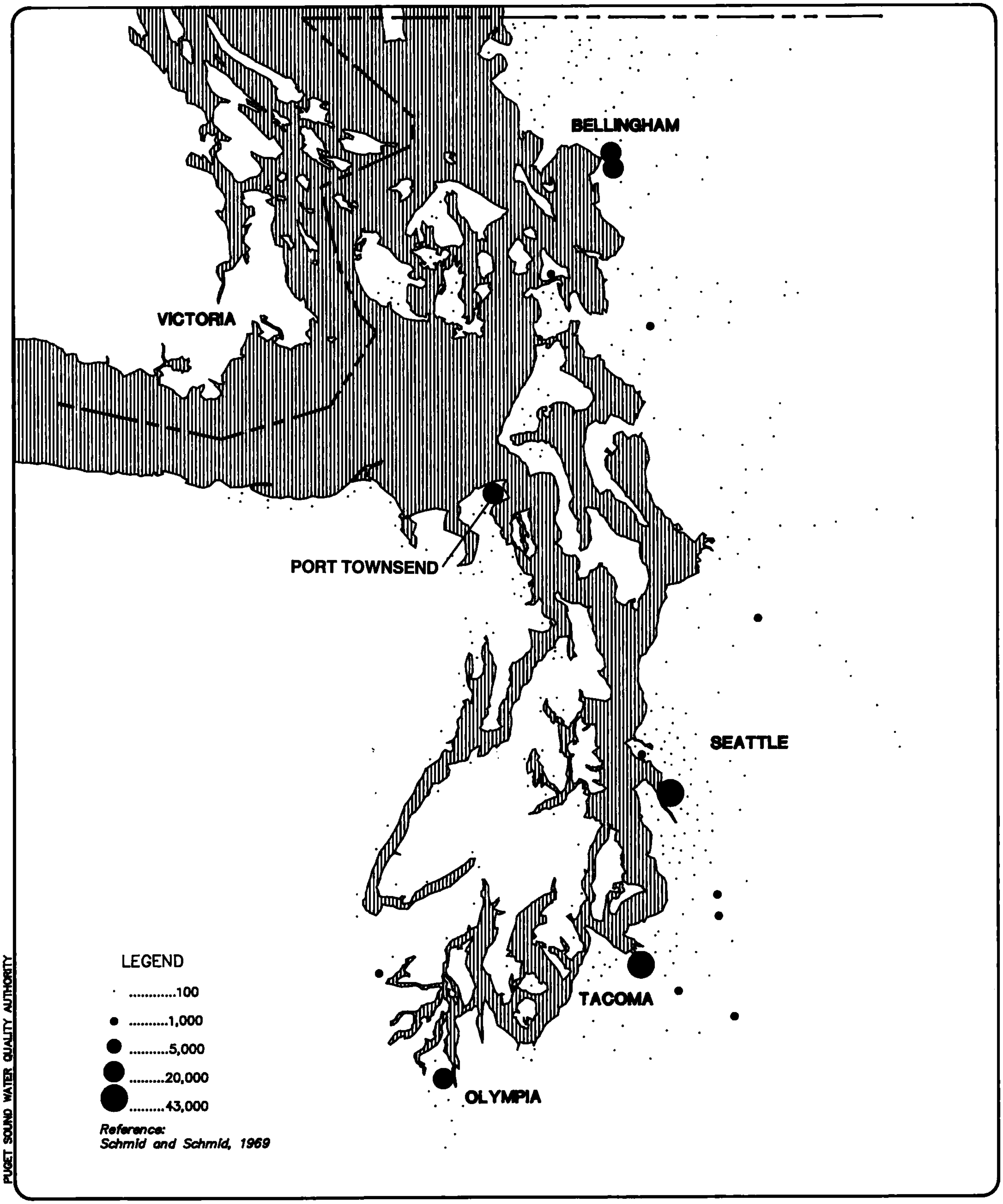
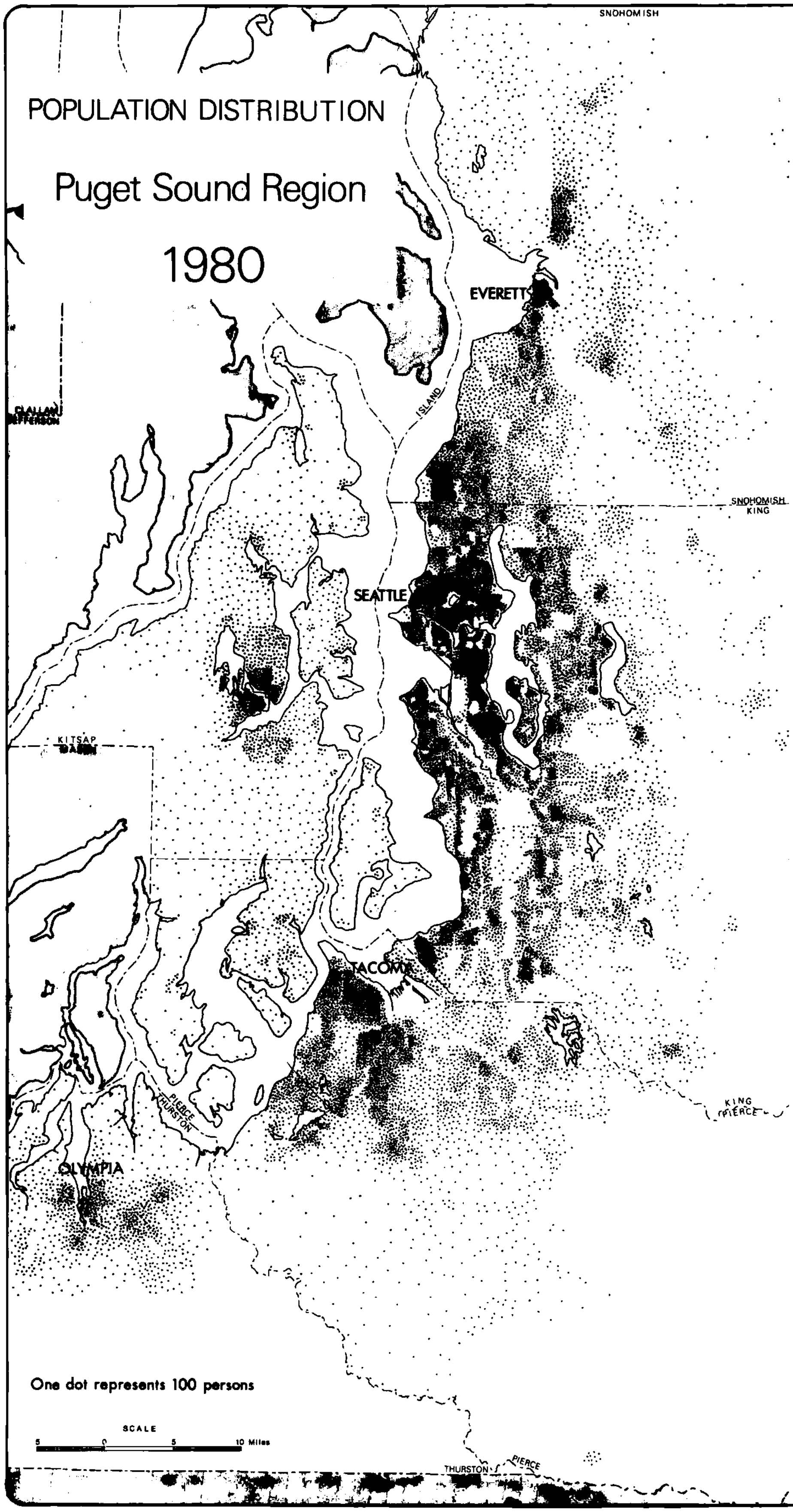


Figure 25

POPULATION DISTRIBUTION IN THE PUGET SOUND REGION IN 1890



LEGEND

Each Dot Represents
100 Persons

REFERENCE:
Mary Stewart, Department of Geography, University of Washington

Figure 26

POPULATION DISTRIBUTION IN THE CENTRAL PUGET SOUND REGION

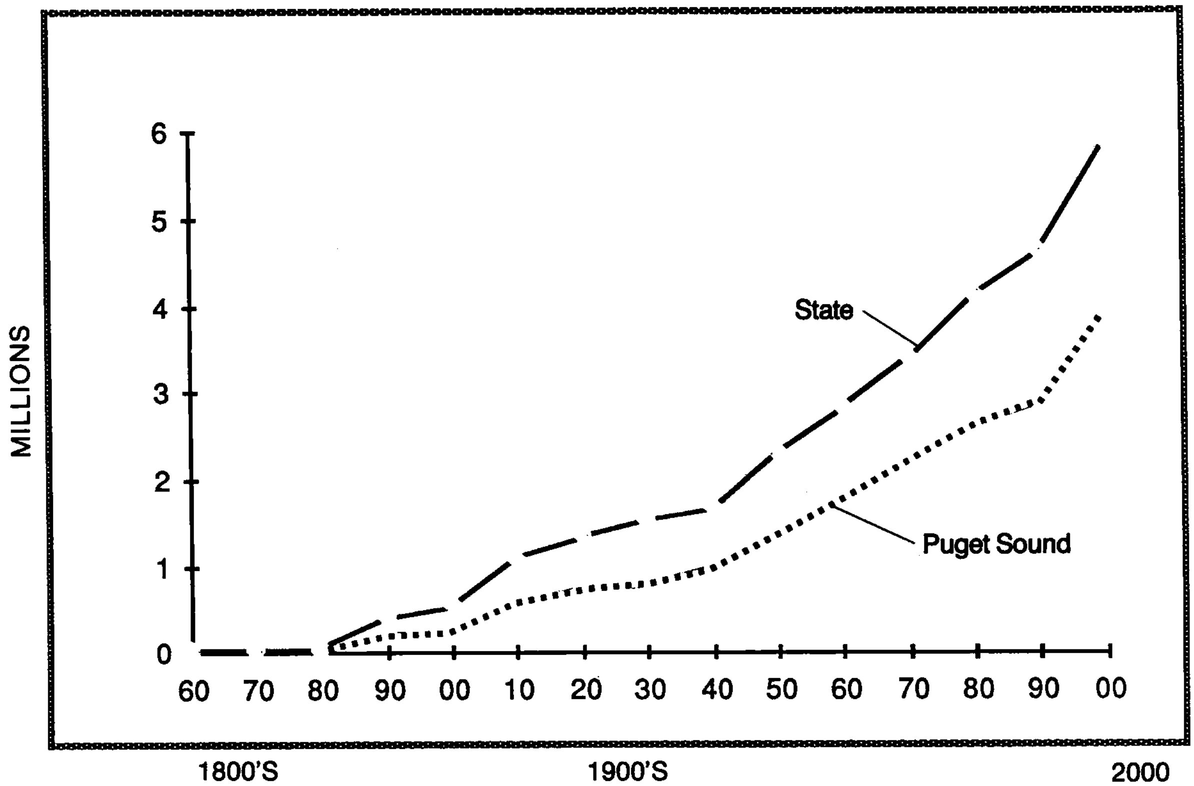


Figure 27

POPULATION GROWTH IN WASHINGTON STATE AND THE PUGET SOUND REGION, 1860–2000

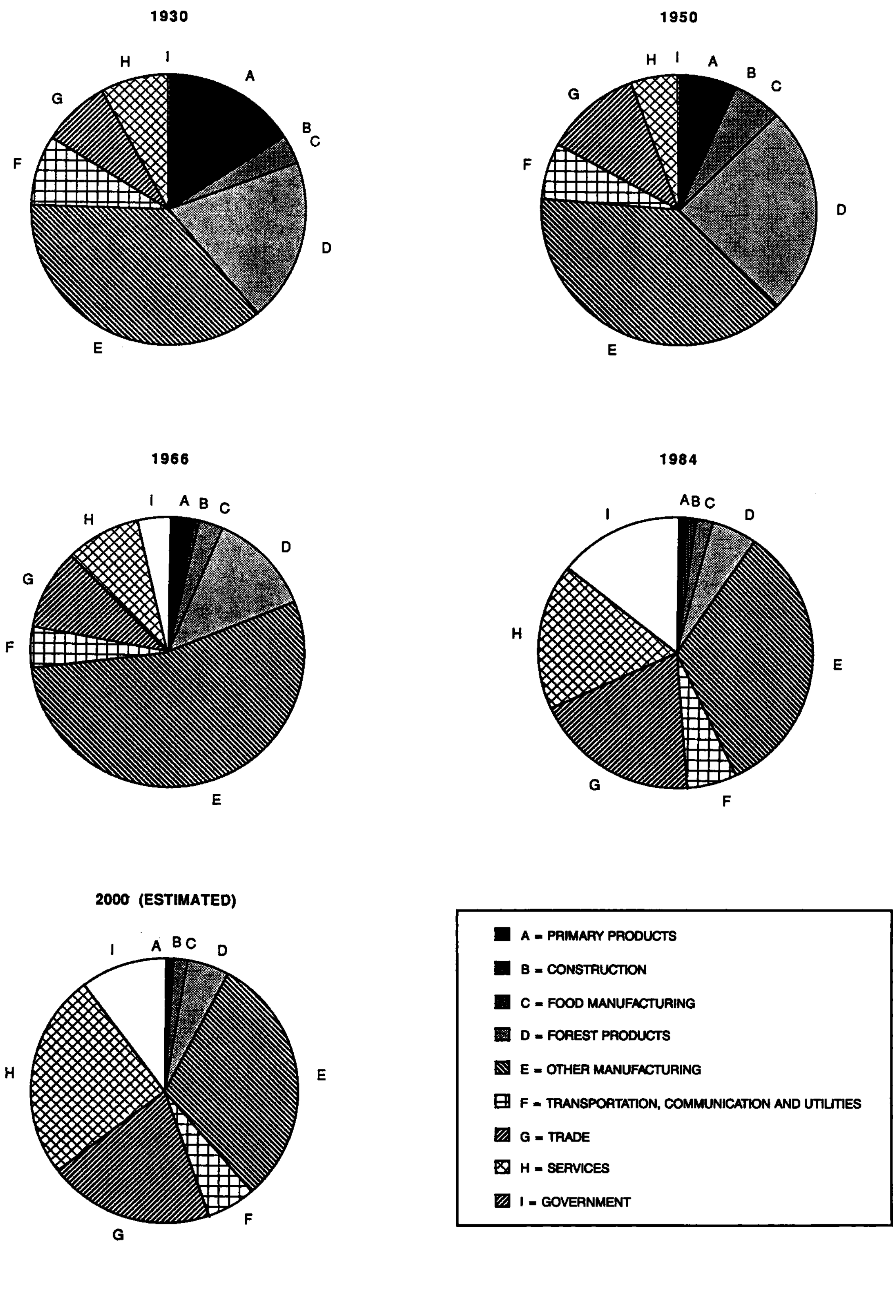


Figure 28

BASIC EMPLOYMENT PROPORTIONS BY CATEGORY IN PUGET SOUND REGION: 1930, 1950, 1966, 1984, 2000 (ESTIMATED)

At the same time, the region's economy became more diversified. Oil refineries were built on Puget Sound starting in the 1950s. A Kaiser aluminum plant was established in Tacoma, and in 1966 the Intalco aluminum company began production at Cherry Point north of Bellingham. Shipbuilding, which had mushroomed during the war, continued to be a major industry in Puget Sound, and companies manufacturing transportation equipment, including PACCAR and Kenworth, became important to the region. This era also saw the growth of the tourist industry, especially during the 1962 Seattle World's Fair.

During World War II major military bases were developed or expanded, including Fort Lewis, McChord Air Force Base, the Bremerton Naval Ship Yard, Sand Point Naval Air Station, Whidbey Island Naval Air Station, and the Keyport Undersea Research and Development facilities. These facilities continued to be major employers--with some fluctuations--during the post-war years. The level of military activity was very high during the Korean and Vietnam Wars, and much shipping activity through the ports was supported by these military activities. In addition, military business became important for the private shipyards, Boeing, and other manufacturers of transport equipment and machinery in the region.

In addition to major changes in the relative importance of various sectors, the overall size of the regional economy expanded rapidly, as shown in Table 4. Total employment grew by more than 50 percent between 1950 and 1966 with particularly strong growth in transportation equipment manufacturing and in the largely non-basic services, trade, and local public sectors.

TABLE 4: EMPLOYMENT BY MAJOR SECTORS, PUGET SOUND REGION

Sector	1950	1966	1984	2000 *(Est.)*
Primary	31,495	24,660	14,076	18,400
Construction	24,952	37,599	55,479	97,500
Food Products	18,737	17,044	15,033	22,000
Forest Products	43,785	38,494	28,524	40,500
Other Manufacturing	62,124	152,984	167,513	244,800
Transportation, Comm. Utilities	32,398	40,947	64,825	92,000
Wholesale and Retail Trade	98,923	144,012	281,586	441,800
Services	57,140	100,502	300,297	552,200
Government (State & Local)	49,415	103,104	132,934	166,000
TOTAL	418,969	659,346	1,060,267	1,675,200

(Reference: Employment Securities Department, Bureau of Economic Analysis)

The geographic distribution of this growth was very uneven among Puget Sound counties. In 1966, the four central Puget Sound counties accounted for 89 percent of the Puget Sound region's employment. They also enjoyed

94 percent of total employment growth during this period. The trend toward greater concentration of regional economic activity in the highly urbanized central Puget Sound region counties has been a long-term trend, continuing in an uneven fashion since the 1920s.

Post-war land development was radically different from earlier settlement patterns. With the construction of freeways and an extensive road and bridge system throughout the region, the distance which people could commute to work expanded greatly. As people commuted to urban jobs from suburban or rural areas with larger lot sizes, the average population density decreased from 8.2 persons per acre before 1960 to only 4.4 persons per acre for development after 1960. The new suburbs, supporting the bulk of the 1.1 million new people living in the four central Puget Sound region counties, also became the location of much new service employment. Shopping malls such as Northgate, Southcenter, Bellevue Square, and Tacoma Mall appeared in previously rural territory and increasingly drew retail trade from traditional downtown business districts. The east side of Lake Washington was transformed from an area of sparsely developed vacation homes into a major bedroom community, and the entire Everett-Seattle-Tacoma corridor became a major metropolitan region. Vacation home development began to accelerate on Hood Canal, Whidbey Island, and the San Juan Islands.

Industrial activity also decentralized during this time period. The Boeing Company illustrates this trend; its industrial capacity moved from the Duwamish River valley to new facilities near Everett, Kent, and Auburn. Many wholesaling and manufacturing facilities sought to expand onto tracts of land larger than those available in older industrial areas. Thousands of acres of productive farmland in the Green, Sammamish, Puyallup, and Snohomish river valleys were converted to industrial uses or to housing.

These pressures from urban development, coupled with stiffened competition from produce from the sunbelt, led to significant declines in the acreage of agricultural land in the Puget Sound region, particularly in King County. Flood control protection provided for the Green River valley made the valley floor attractive for commercial and industrial purposes and, as cities annexed the area, zoning changes encouraged non-agricultural land uses.

The best data on land use in this period derive from the Puget Sound and Adjacent Waters Study (PSAW), the only basin-wide assessment of land use that exists, which was sponsored in the mid-1960s by a variety of federal and state agencies to assess water resources needs and issues. Figure 29 (taken from this study) shows broad classes of land use in the Puget Sound region in the mid-1960s. At the time of the study, most of the land in the Puget Sound basin was in forest use. Urban settlement occupied only a very small fraction (five percent) of the land area of the basin. The land shown as farmland is divided between cropland and rangeland with cropland accounting for about one-third of the acreage used for agriculture in 1966. (Rural non-farm use includes river wash tidelands, mines, farmsteads, and rural non-farm residences.) The Adjacent Waters Study estimated that about 24 percent of the land within the built up areas was used for housing, about 10 percent for commercial and industrial purposes, and about 28 percent for

streets, highways, parks, schools, and other public uses. The balance was vacant land, or airports, intercity roadways, and railroads.

1970 TO 1985: DAWN OF THE POST-INDUSTRIAL AGE AND THE SERVICE ECONOMY

Contrary to early predictions of an era of industrial growth, the 1970s began badly for the regional economy. The Boeing work force dropped precipitously between 1969 and 1971 due to adverse business conditions. Simultaneously, the forest products industry entered a slump due to high domestic interest rates adversely affecting the construction industry. The forest products industry has yet to fully recover. In contrast to the post-World War II years when the growth of manufacturing led the expansion of the Puget Sound regional economic base, the period since the "Boeing bust" has seen more diversified growth in the economic base. Service industries now play a far more important role than they have at any time in the region's history.

The local aerospace industry revived in the late 1970s, and current local aerospace employment is about 75,000. Other high-technology industry, including electronics, instrumentation, biomedical equipment, computer software, and machinery, has also developed in the region. Much of this growth has occurred on the east side of Lake Washington and in south Snohomish County.

The federal government's decision to construct the Trident support facility in Bangor led to a major expansion of employment and population in Kitsap County, and military activity at other key bases in the region has remained at high levels, although below the peak levels of the Vietnam War.

In addition to feeling the pressure from interest rates, forest products employment has suffered as technological changes diminished labor requirements. Competition from Canada and the southeastern United States stiffened during this period. The export market for raw logs has suffered a recent decline. These factors taken together have helped to produce high levels of unemployment in Puget Sound communities dependent upon the forest products industry. However, there are some signs of optimism in this industry. Although forest products employment has declined, annual timber harvest in the Puget Sound region remained at about two billion board feet in the 1970s and 1980s. Log exports to Japan and Korea for construction have expanded dramatically over the past 15 years, reaching one-third of total timber harvests by 1980.

As a result of recent trends in economic development, the relative importance of resource-based industries is much greater in the rural counties of the Puget Sound basin than for the urbanized central Puget Sound counties, as shown in Table 5.

Figure 28 and Table 4 show that service employment has become the largest component in the regional economic base. For example, thousands of research-related jobs at colleges and universities are supported by grants and contracts from sources outside the region. The strong growth of services in the regional economic base is concentrated almost entirely in the central Puget Sound region.

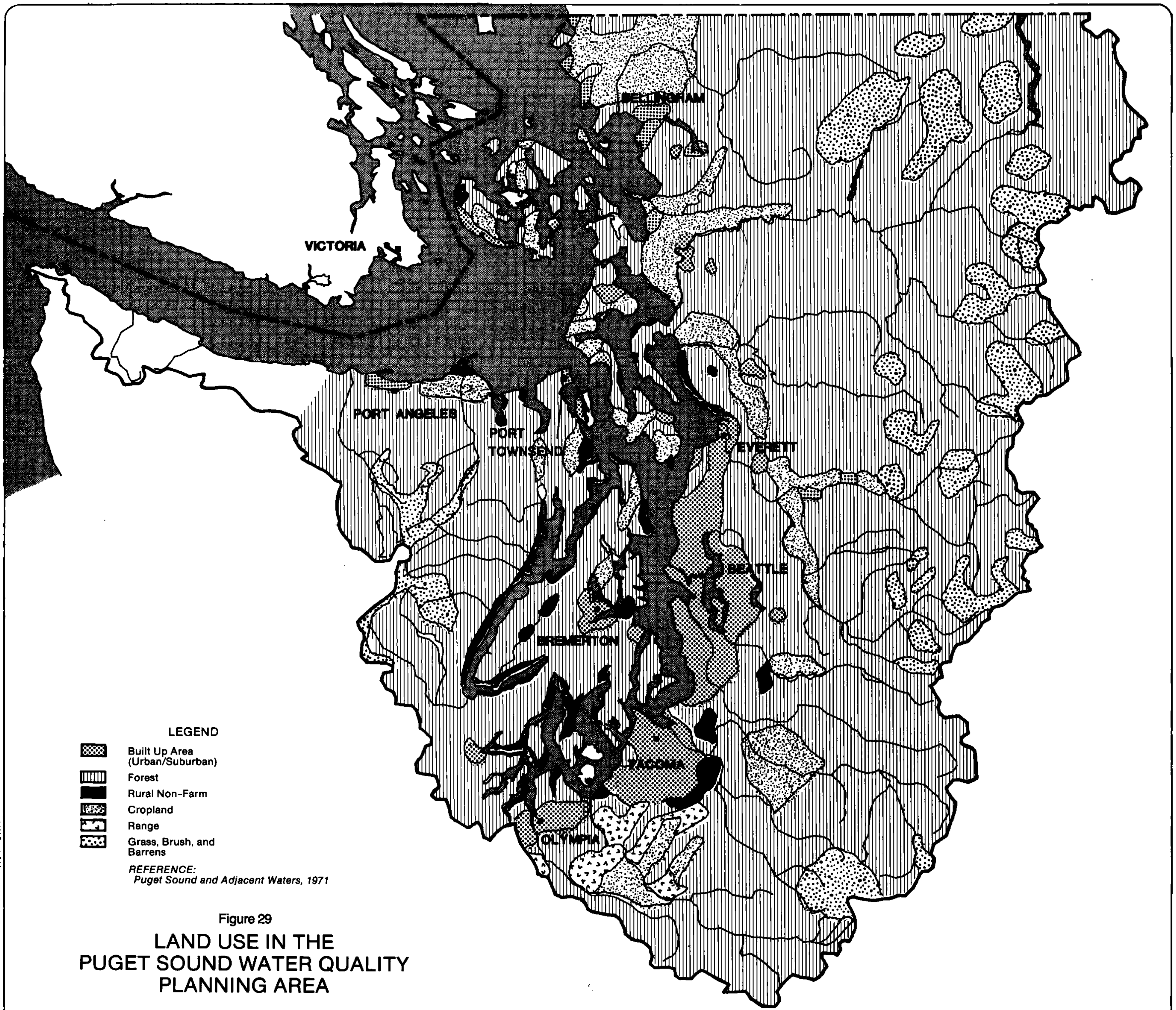


Figure 29

LAND USE IN THE PUGET SOUND WATER QUALITY PLANNING AREA

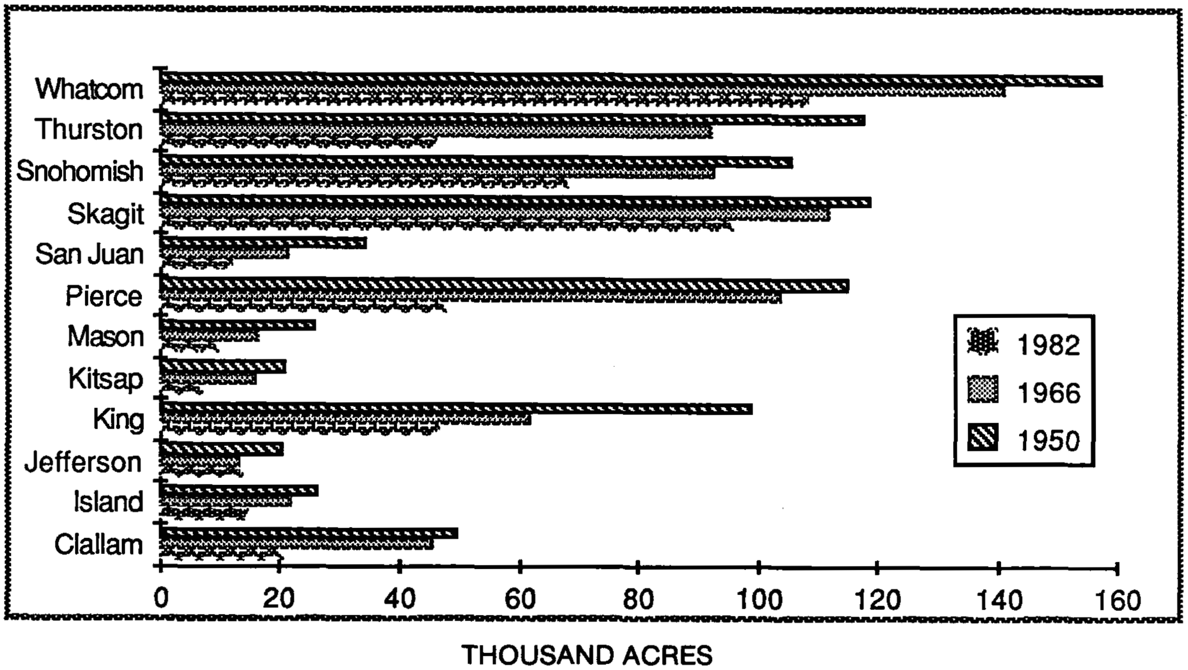


Figure 30

CHANGES IN TOTAL AGRICULTURAL ACREAGE (RANGELAND PLUS CROPLAND) FOR THE PUGET SOUND COUNTIES FROM 1950 TO 1982

TABLE 5: COMPOSITION OF THE 1984 ECONOMIC BASE (%)

	Percentage of	
County	Rural Counties	Central Puget Sound
Primary	4.6	1.0
Construction	1.1	1.0
Food Products	3.9	1.6
Forest Products	16.1	4.2
Other Manufacturing	16.6	34.9
Transportation, Communications, Utilities	5.2	6.0
Trade	30.5	18.2
Services	13.8	18.2
Military	8.2	14.9
TOTAL	100.0	100.0

The population of the Puget Sound region is currently estimated at 2.9 million. Population growth in the Puget Sound region has slowed during the past 15 years, and the populations of central cities have actually declined. However, suburbanization has continued. Since 1960, Seattle has lost population to suburban cities and unincorporated areas, and growth has slowed in Tacoma, Everett, Bellingham, Bremerton, and Port Angeles. Figure 26 presents the distribution of population in parts of the Puget Sound basin in 1980.

Since 1910, about 50 percent of the region's population has lived in King County, but that percentage decreased slightly (to 47.3) in 1980. Pierce County has retained 18 to 19 percent of the region's population since 1910. Within the past three decades, Snohomish County has increased its share from 7.9 to 12.6 percent of the region's population.

The fastest rates of growth have taken place in "amenity areas" or where population is not associated with basic employment. For example, the population of San Juan County more than doubled (from under 3,900 to more than 7,800) during the 1970s. The next fastest growing counties were Island (up 63 percent from 27,000 to 44,000) and Thurston (up 62 percent from 77,000 to 124,000). Population growth in Thurston County primarily reflects expansion of state government. San Juan and Island Counties are rapidly growing areas of vacation and retirement homes, but the absolute numbers of people are very small. San Juan County's dramatic growth rate of the 1970s only increased its regional population share from 0.2 to 0.3 percent. (During the same period the share of Kitsap County increased from 4.5 to 5.5 percent and that of Thurston County from 3.4 to 4.6 percent.) Although King and Pierce Counties grew much more slowly than the outlying counties during the 1970s, at 10 and 18 percent respectively, their growth in absolute numbers was the most significant in the region. King County grew by 110,000 (from 1.16 to 1.27 million), and Pierce County grew by 64,000 (from 422,000 to 486,000).

No comprehensive study of land use in the Puget Sound region has been made since the Puget Sound and Adjacent Waters study of the 1960s. Some pieces of historical information can be used to estimate changes in land use over the last two decades. For instance, the Puget Sound Council of Governments (PSCOG) has made estimates of land used for housing and economic activity in the central Puget Sound region.

Using these and other data on employment and population in the central Puget Sound region, estimates of land use can be made for the early 1980s (Table 6). Comparing these estimates to those for 1966, it appears that intensively used urban land has almost doubled from 337,000 to 651,000 acres. The combined acreage of forested and rural non-farm land appears to have decreased by about 100,000 acres. An estimate of the total increase in urban and rural residential land can be obtained by assuming that the ratio of rural non-farm to intensively used urban land has remained constant since 1966, as population and employment increased to their 1980s values. This yields a current estimate of 350,000 acres of rural non-farm land in the Puget Sound basin (Table 6) and this corresponds to an increase in high-density urban and rural non-farm settlement from 577,000 acres to about one million acres (an increase of over 70 percent) in the last 20 years. Given the strong rates of amenity growth in the northern Sound and the sprawling settlement pattern, this appears to be a reasonable estimate. Of the forest land use, approximately 50,000 acres are harvested per year.

Farmland acreage has continued to decline during this period, as shown in Figure 30, although less rapidly than in the earlier post-war period.

TABLE 6: ESTIMATED LAND USE IN THE PUGET SOUND WATER QUALITY PLANNING AREA BY CATEGORY IN 1984 AND YEAR 2000 IN THOUSANDS OF ACRES

	1984	2000
Intense Urban	509.3	823.9
Pastureland	248.8	248.8
Cropland	245.8	245.8
Streets and Highways	273.5	273.5
Rural, Non-Farm	270.0	466.9
Forest	7009.3	6497.8
TOTAL	8556.8	8556.8

THE FUTURE: LOOKING TO THE YEAR 2000

The next several decades promise to be a time of modest growth for the Puget Sound region, in contrast both to the boom periods earlier this century and from World War II to 1970 and to the intervening recessions. Recent economic forecasts from the Federal Bureau of Economic Analysis for the most urbanized counties, modified to represent the economy of the Puget Sound basin as a whole, can be used to estimate the total employment, basic employment, and the composition of employment in the year 2000 (Figure 28 and Table 4). In contrast to data for 1984, it is evident that the services are anticipated to be

the largest source of jobs, followed by expansions in manufacturing and trade. Other anticipated trends are a strong aerospace business for the Boeing Company, expansion of international trade through Puget Sound ports, continued development of high-technology industry, new economic activity resulting from research activity at the region's colleges and universities, and the continued development of services as a basic sector in the economy.

Small high-technology firms may expand to locations such as the "technology corridor" from Everett to Redmond, much as manufacturing and warehousing spread to the Green River valley in the post-war years. At present, there is little evidence to suggest dispersal of this rapidly growing component of the economic base to the more rural parts of the basin.

The forecasts shown in Figure 28 suggest a slight recovery in employment levels in the currently depressed forest products industry. However, these forecasts may be too optimistic. A recent assessment concluded that future harvest levels in western Washington (particularly from private lands, which are currently a major source of timber in the Puget Sound region) would be below those in the recent past. National forest timber harvests may also be limited due to increasing pressures for their recreational use in Western Washington. Technological change in timber processing is expected to continue to reduce demands for labor, creating problems in communities dependent upon employment in the forest products industry.

Population estimates for 1985 and forecasts for 1990 and 2000 have been made by the Washington State Office of Financial Management (Figure 27). These data are presented by county in Figure 31. The population of the Puget Sound region is forecast to grow from the current 2.9 million to 3.0 million in 1990 and to between 3.7 and 3.9 million by the year 2000. Employment is expected to expand from 1.2 million to 1.8 million during the same period. These estimates suggest that the Puget Sound basin will account for a roughly constant 66 percent of the state's total population.

The region's population density is expected to continue to decrease through the end of the century as a result of smaller families and larger lot sizes. Much of the employment growth in non-basic services is anticipated in low-density shopping centers. Hence, there is an overall trend toward relatively more land being developed per person. A forecast of land use in the year 2000 can be made (Table 6) given assumptions that the acreages of highways, railroads, and waterways are fixed and that acreage of agricultural land will remain roughly constant (recent declines in pastureland may be offset by public policies designed to preserve agricultural lands). This forecast suggests that almost 1.5 million acres or 18 percent of the land in the Puget Sound region will be in intense urban or rural non-farm use by the year 2000. Most of this intensively used land would be in the central Puget Sound region.

These forecasts have tremendous significance to planning for regional water quality. A population increase of 31 percent will be accompanied by a 62 percent increase in lands developed for intense urban activities and a 70 percent increase in lands developed for rural non-farm use. No increase is projected in agricultural land use and, along with a minor percentage decrease

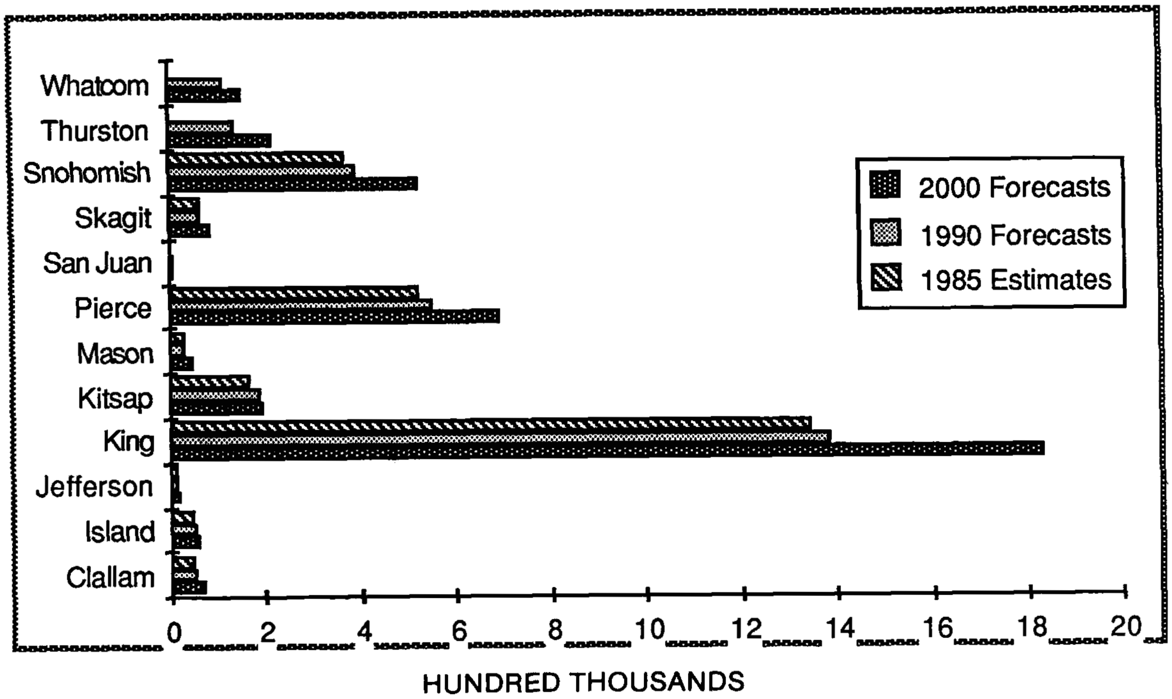


Figure 31

1985 POPULATION ESTIMATES AND 1990, 2000 FORECASTS FOR THE 12 PUGET SOUND COUNTIES

[Reference: U.S. Census]

in land in forest use, there will be a decrease in forest harvest activities. Employment and economic activity are projected to shift increasingly to services, government, trade, and construction. Thus, residential, commercial, office, and retail land uses will grow. Heavy industrial activities such as pulp and paper and smelting are not projected to increase significantly.

LOSS OF WETLANDS

One major environmental consequence of human alteration of the Puget Sound basin has been the destruction of wetlands through development.

DEVELOPMENT OF WETLANDS

In much of the Puget Sound area, the earliest wetland development took place in estuarine wetlands which were diked, drained, and filled for agriculture. Wetlands were chosen for agricultural development because they yielded some of the only accessible flat land with deep tillable soils in western Washington. This type of development took place mostly near the turn of the century and has not significantly expanded in area since the 1920s. Many of the areas that have been pastured rather than tilled have retained some of their wetland qualities and still remain a valuable wildlife resource.

Some coastal wetlands were developed for ports and industrial sites instead of agriculture. These areas were dredged and filled rather than diked, and portions of these areas often were left unfilled to use for log storage. In recent years, log export has remained a major industry that has required more handling areas near water, but logs are often now stored on dry land (which is often a filled wetland). As these changes occurred, areas formerly used for in-water log storage were filled, completely eliminating the wetland.

In the areas that became industrialized, agriculture was established farther up rivers where banks were diked to protect farmlands, homes, and rural communities from flooding. Dams were constructed upstream in some areas to regulate flooding.

The recent expansion of urbanization has created new pressures on wetlands in remaining river valleys. Prior to the 1970s, suburban wetlands were frequently used as garbage dumps. Since the mid-1970s there has been a major trend toward development of warehouses, subdivisions, and office and high-technology industrial areas in the agricultural valleys close to urban centers. Those pastured or crop areas that still had some value as wetlands were virtually eliminated.

In contrast to tidal and river bottom wetlands, lakeshore wetlands of western Washington recently have been developed almost exclusively for residential purposes. Waterfront areas that a generation ago were settled only with summer homes have been incorporated into nearby cities. Residential development may include: bulkhead construction and filling to establish a yard; clearing and minor filling with sand to create a beach; minor dredging for boat access; or simply continual mowing to create a lawn. In each case the alterations may be minor, but the cumulative effect is elimination of wetlands along most, if not all, of the lakeshore. In contrast, the lowering of Lake

Washington in 1917, at the time of the Montlake cut, increased shallow marshland areas like Union Bay and Juanita Bay.

Wetlands have been lost along the beaches of most urban Puget Sound areas where filling and bulkheading were common through the late 1970s. Not only has residential development contributed to the loss of wetlands at the mouths of small streams and in coves, it has significantly modified littoral drift (the movement of sand or other sediment types along the shore). The construction of bulkheads along many shoreline areas has significantly reduced the supply of sediment available for littoral drift. Because of this loss, some new sandspits have been built up and others have been lost, and banks have eroded. These changes have created an inferior environment for spawning herring and smelt, crabs, clams, and oysters.

A more recent trend of land development is occurring on the hillsides of rural areas surrounding suburban communities. Residential development, especially multiple-unit construction, has increased losses of wooded wetlands--particularly those not directly associated with streams.

The most recent trend in management of wetlands is mitigating or compensating for their loss. Since 1980 mitigation--including the creation of new wetlands or enhancement of existing wetlands--has been attempted as a part of a number of projects. Because of the novelty of this effort, its effects have not yet been clearly demonstrated.

ESTIMATED LOSSES

A comparison of current and historical coastal wetland areas at selected river deltas is shown in Table 7. Eight of 11 major river deltas show a loss of coastal wetlands; three deltas show wetland losses of 1,200 acres (five square kilometers) or more. Of the approximate total of 22,500 acres (91 square kilometers) of coastal wetlands present in 1800 in the 11 deltas, nearly 13,500 acres (55 square kilometers) have been converted to other land uses.

Areas where marine wetlands have been altered which are not included in Table 7 are Budd and Hammersley Inlets, the mouths of the rivers on the west side of Hood Canal (other than the Skokomish), and the wetlands near Belfair. When combined with Table 7, the total acres of existing wetlands is increased to approximately 23,000 acres (93 square kilometers) with a net loss of over 14,300 acres (58 square kilometers) resulting from human activity.

Since there are no reliable figures for wetlands in valley bottoms, their losses have been defined by percentages. In stream corridors (such as the Snoqualmie River valley) where pasturing is continuing, there has been a 50 to 60 percent loss of wetlands. In areas where farming takes place (such as the Skagit Valley), there has been a 90 to 95 percent loss. Areas that have been or are becoming commercially developed (the Green and Puyallup Rivers) have sustained losses in excess of 95 percent. The only remaining wetlands in some areas are open drainage ditches. In other areas all drainage is through underground pipes, and all wetlands have been lost (100 percent).

TABLE 7: COMPARISON OF HISTORICAL AND PRESENT-DAY WETLAND AREAS AT SELECTED RIVER DELTAS

	Estimated Area of Wetland (in Acres)		
River Delta	Historical	Present-Day	Increase or Decrease
Nooksack	1110	1135	2%
Lummi	1435	75	-95%
Samish	470	100	-79%
Skagit	3955	2965	-25%
Stillaguamish	740	890	20%
Snohomish	9635	2470	-74%
Duwamish	640	10	-98%
Puyallup	2470	125	-95%
Nisqually	1410	1015	-28%
Skokomish	520	345	-34%
Dungeness	120	120	0
Totals for Mapped Area	22505	9250	-59%

(Source: Bortleson et al.)

MODERN WATER DEPENDENT ACTIVITIES

The value of the waters and habitats of the Puget Sound basin can be represented by the uses made of them. These activities are called "water dependent". Key water dependent activities include ports and shipping, maritime recreation such as boat launching and fishing, wet moorage (although dry moorage has recently proliferated), fishing and aquaculture, shipbuilding, and aesthetic appreciation of the Sound. The economic importance of several key water dependent activities is discussed in this section.

MARINE SHIPPING

Puget Sound has always played a key role in the commerce of this region, serving as a transportation medium for local economic activity as well as for international and interregional shipping. Since World War II there have been major changes in both the nature and magnitude of maritime commerce on Puget Sound and the technology used for cargo movement.

In the early 1950s (1953), marine transportation on Puget Sound was dominated by movements between local ports (Table 8). The principal cargoes were rafted logs (3.8 million tons), sand and gravel (1.9 million tons), and refined petroleum products (0.9 million tons). Logs were commonly dumped into waterways and rafted to processing sites around the Sound. Rafted logs

dominated incoming shipments to Port Angeles, Shelton, Olympia, Everett, Anacortes, and Bellingham. Most sand and gravel was shipped to the major urban ports--Seattle, Tacoma, the Lake Washington Ship Canal, and Everett. Refined petroleum products were imported to the urban ports from California; then a portion was loaded onto barges and distributed to smaller ports around the Sound. Approximately half of the tonnage moving through the Port of Seattle in this period was petroleum products.

TABLE 8: TONNAGE OF MARITIME SHIPPING IN PUGET SOUND FOR 1953, 1968, AND 1983

(Tons in Millions)

	Total	Foreign		Coastal		Internal		
Year	Tonnage	Imports	Exports	Recp.	Ship.	Recp.	Ship.	Local
1953	29.73	1.75	1.42	6.47	1.32	9.50	5.48	3.79
1968	46.64	5.50	6.62	5.29	3.66	14.28	6.32	4.97
1983	51.22	10.73	15.30	5.96	4.90	7.06	4.20	3.07

Foreign trade and coastal trade (between Puget Sound and other U.S. ports) accounted for only about one-sixth of the tonnage moved through the Sound in 1953. Coastal trade was dominated by lumber and other forest products. International exports were dominated by wheat, and imports included ores coming to smelters in Tacoma and pulpwood and fuel headed for mills in Bellingham, Port Townsend, and elsewhere. Movements of general cargo through the major urban ports were relatively small, representing about 10 percent of the total tonnage through the Port of Seattle in 1953.

By 1968 major changes had taken place in the structure and magnitude of marine commerce on Puget Sound (Table 8). Total movement increased to 47 million tons in 1968 from approximately 30 million tons in 1953. The most important segment of this increase was in foreign cargo traffic which increased dramatically to more than 12 million tons from about three million tons in 1953.

Total cargo movements on Puget Sound rose to over 50 million tons in 1983 (Table 8), twice the 1953 levels and more than 25 percent above the boom years of the late 1960s. The most impressive aspect of this change is an enormous expansion of international trade. International cargo movements have more than doubled since 1968 from about 12 million to over 26 million tons. Although logs and chips still contributed the largest fraction of export tonnage, the growth of container cargo traffic from the major urban ports has been substantial.

In 1983 the major commodities shipped were: crude oil (12.2 million tons plus 1.2 million tons of residual fuel oil and 0.6 million tons each of distillate fuel oil and gasoline--a total of 14.6 million tons of petroleum products); sand and gravel (1.6 million tons); logs (0.8 million tons); and other cargo (1.3 million tons). In addition to these movements, 18.3 million tons were recorded by the Corps of Engineers as cargo movements on Puget Sound in 1983. Although

data assigning these movements to sources are not available, most were probably internal or local, accounting for the difference between total internal receipts at these major Puget Sound ports and reported shipments from them. The crude oil shipments likely represent inbound foreign or coastal traffic.

Traffic among Puget Sound ports dropped between 1968 and 1983 to roughly 1953 levels. This drop may reflect the depressed state of the forest products and construction industries in 1983--sand and gravel and log shipments were well below 1968 levels. Petroleum product movements from Seattle were also lower, reflecting the closing of some petroleum wholesaling establishments in the Seattle harbor. However, shipments from the four refineries located in the north Sound continued and represented the largest volume of internal shipments in 1983.

A recent forecast suggests that foreign cargo movements could increase from the 26 million tons of 1983 to at least 40 million tons by the year 2000. This number does not include imports of crude oil or estimates of export of wheat or feed grain.

Although no Sound-wide analyses have been completed for the impact of port activity on the economy, the Port of Seattle recently estimated that harbor operations lead directly to 24,000 jobs and, through multiplier effects, to a total of 37,000 jobs in King County and 54,000 jobs statewide. Given the Port of Seattle's share of container cargo traffic through Puget Sound ports (about half of all such movements) and the reduced demands for labor associated with shipping of bulk commodities such as logs or wheat that tend to dominate shipments through the other Puget Sound ports, it is reasonable to assume that the regionwide impact of port activity is probably about double that measured by the Port of Seattle or about 100,000 jobs statewide. This is about five percent of total statewide employment at the present time.

FISHERIES

The harvest of fish and shellfish has been one of the most important human uses of the Puget Sound basin for as long as there have been people in the basin. Each species has a certain natural abundance, but even without the effects of human activities, populations will fluctuate greatly from year to year as a result of climate, ecological competition and predation, and natural events such as the eruption of Mount St. Helens in 1980 and the El Nino event in 1982-83. The tools developed to capture these marine resources are efficient enough that it is possible to overharvest virtually every species present. In addition, destruction of habitats for spawning and larval rearing in rivers and lakes and the loss of nearshore estuarine wetlands, including salt marshes, has probably had a profound effect on salmon production as well as surf smelt and herring. Degradation of saltwater by toxic contamination and other factors such as depletion of dissolved oxygen have historically contributed to fishery losses. It is impossible to separate the effects of natural fluctuation, overfishing, and pollution for species that are extensively harvested. The following section discusses the harvest trends of the major resources and summarizes their recent economic importance.

Knowledge of trends in the availability of major commercial and recreational fish species in Puget Sound is limited by several constraints. Historical data

are available only for fish catch and not for absolute abundance. Trends in catch reflect not simply changes in abundance but also in the harvesting effort expended. The effort directed at a particular fishery depends on weather, changes in technology, fluctuations in conditions in the market place, and management decisions. Natural phenomena such as changes in migration patterns can also affect catch and give the false appearance of a change in fish abundance.

The Puget Sound fishing industry is an important part of the state's fishing industry, although it is very small compared to the region's other resource-oriented basic industries. The total value of all commercial and recreational fish and shellfish was estimated at $74 million in 1984.

This total value is broken down by categories of fish and shellfish (Table 9). Salmon harvests represent the bulk of the value of the Puget Sound catch. Groundfish (cod, hake, pollock, rockfish, surf perch, dogfish, sole, and flounder), herring, and shellfish (clams, oysters, crabs, scallops, mussels, abalones, shrimp, geoducks, octopus, and squid) account for the rest.

TABLE 9: ESTIMATED 1984 VALUE OF PUGET SOUND FISHERIES

Fishery	Annual Value
Commercial Salmon	$26.7 million
Sport Salmon	28.8 million
Herring, Smelt	.3 million
Commercial Groundfish	3.6 million
Sport Groundfish	1.5 million
Commercial Shellfish	9.4 million
Sport Shellfish	3.6 million
TOTAL	$73.9 million

(Sources: Solomon and Mills, 1983; WDF, 1984)

Salmon

Reliable data on the harvest of salmon in Puget Sound date only from the early part of the 20th century. Figures 32 and 33 present commercial landings of total salmon and coho. The high number of landings between 1913 and 1920 may represent overfishing that drove the stocks into a decline. In addition, recreational catches are not included in the figures but have increased greatly over this time period. The present harvest also is dependent on a large and sophisticated hatchery system. Without artificial propagation, present catch levels could not be continued. There is no question that natural salmon production is far below what it was before extensive development of the Puget Sound basin. Overfishing is believed to have played a role in this decline, but destruction of spawning and rearing habitat by logging, dam and lock construction, and development of salt and freshwater shorelines is believed to have had the most serious impacts.

Currently, catches of salmon species from the Sound are relatively stable. This stabilization has been accomplished in part by stringent management measures that include careful limitation of catch for all species and frequent closures of entire fisheries. Salmon populations are managed to ensure adequate numbers of returning spawners (the escapement) for reproduction. Legal and socioeconomic factors have affected management and allocation of the Puget Sound salmon fishery in recent years. The Boldt decision in Federal court in 1974 allocated half of all state salmon resources to Native Americans. Because of the allocation of salmon harvesting rights between Indian and non-Indian fleets, the management structure for salmon has changed rapidly. In 1985 the Puget Sound Salmon Management Plan was adopted. This is a comprehensive management plan for Puget Sound salmon that integrates Indian and non-Indian management activities. Also in 1985 the United States and Canada entered into a treaty that covers harvest and management of international salmon resources that commingle in offshore waters and the Strait of Juan de Fuca. Again, Indian and non-Indian fishing interests are equal partners in management of the stocks. These developments appear to promise more effective management of the salmon resource in the future.

An equally important strategy to mitigate habitat destruction has been the artificial enhancement of spawning success by means of hatcheries. Chinook and especially coho fisheries in the Sound have been heavily supplemented by hatchery production, and sport and commercial catches of these species have been increasing for roughly the last two decades (Figures 32 and 33). Again, the tribes are playing an active role in hatchery production of salmon. However, there currently is concern that continued hatchery production is occurring at the expense of the remaining wild stocks because the hatchery fish, when released into open water, are released at a size and in such numbers that they displace or even eat the natural fish. In addition, there is concern that the special breeding used to refine hatchery stocks may reduce the genetic diversity of the salmon species, leaving them susceptible to epidemic disease or other catastrophe.

Salmon are the most important species group of the commercial and sport fishery in Puget Sound. Estimated recent (1974-1978) average annual commercial salmon catch for all species migrating through the Strait of Juan de Fuca (including Fraser River stocks) is 117,000 tons. Sport catch is estimated at 800 tons in the Strait of Juan de Fuca and at 1,600 tons in the Main Basin (or about two percent). The value of the commercial salmon catch was $26.7 million in 1984. The value of the sport salmon fishery was estimated at $28.8 million in the same year. Sport and commercial catches are valued differently, the sport catch being valued by the estimated amount people spent on food, lodging, gear, and boat fees to catch their fish, and the commercial catch valued on the price per pound paid at the boat.

Baitfish

Herring is the dominant baitfish in terms of abundance and catch in Puget Sound. The commercial herring catch has three components: a sac-roe fishery (in which the eggs are collected), a general purpose fishery, and a bait fishery.

Herring catches in Puget Sound were quite low until 1957 when the general purpose fishery was begun. The fishery was conducted during fall and winter

in the eastern Strait of Juan de Fuca and San Juan Islands area (especially in Bellingham Bay), catching both fish originating from the Strait of Georgia and a newly discovered stock from central and southern Puget Sound and Hood Canal. The catch was used for production of fish meal and oil, as food for zoo animals, and as bait for king crab in Alaska. The size of the catch varied considerably over the next two decades (Figure 34) but showed somewhat of a downturn beginning in the 1970s. After careful monitoring and several attempts at management measures to stem the decline, the fishery was closed in 1983. A decrease in the average size of the fish caught indicated that overfishing was occurring. This fishery is not expected to reopen in the near future.

Catches of the sac-roe fishery during spring in the southeastern Strait of Georgia (averaging 2,000 to 4,000 tons per year) and the year-round bait fishery in the central and southern Sound (600 tons per year) were stable until 1980. In 1980 the sac-roe fishery was closed by the Canadian government due to low populations of surviving young (recruits).

Juvenile herring are taken in a recreational bait fishery in the Sound.

In addition, a small commercial surf smelt fishery averages 37 tons per year taken mostly from Saratoga Passage. Smelt are also taken recreationally in that and other central Sound locations.

Groundfish

Groundfish are fish that are captured by trawl nets on or near the bottom. This group includes the gadids (cod family: hake, pollock, and cod); the rockfish and surf perch; the flounder and sole species of flatfish; and the spiny dogfish. Cod, English sole, and starry flounder historically have dominated the groundfish catch from Puget Sound. English sole dominates the commercial catch from the central Sound and Hood Canal, and cod and pollock dominate the catch in the outer waters of the Strait of Juan de Fuca. Total groundfish yield has increased steadily in the last 20 years to roughly 5,000 tons annually. Over the last decade hake, pollock, and dogfish have increased as a fraction of the total weight of catch, but this may reflect changing fishing habits as much as changing abundance.

The commercial catch of flatfish has followed a fluctuating upward trend since the 1920s (Figure 35). English sole is the dominant species in this group. Much of the recent increase in catch of English sole is attributed to increased fishing effort. Catch per unit of effort, an indirect measure of population status, is stable in most areas of the Sound. However, catch of English sole per unit of effort is decreasing in the central Sound, a possible indication that overfishing or some other detrimental factor such as contamination may be occurring in this area. The commercial groundfish harvest was valued at $3.6 million in 1984.

Recreational groundfish catches are estimated at 1,000 tons per year. A small but popular part of the recreational groundfish catch, the sport fishery for lingcod, was closed on the inner Sound in 1978 and restricted in outer waters due to declining catches. The fishery was reopened in 1983, and studies are currently underway to determine appropriate management measures to prevent

future closures. The recreational groundfish harvest was valued at $1.5 million in 1984.

SHELLFISH RESOURCES

Tribal, commercial, and recreational shellfish resources in Puget Sound include molluscan bivalves (oysters, hardshell clams, mussels, scallops, and geoducks), octopus, squid, and crustaceans (crab and shrimp). As with finfish, there is often no straightforward relationship between population abundances of these species and their harvests which are influenced by market conditions. Populations of intertidal clams and oysters are much easier to assess than those of fish, since the animals are immobile and easily accessible. This immobility, and the fact that bivalves feed by filtering large amounts of water and particles, make natural populations highly sensitive to the impacts of contamination and other sources of environmental degradation. However, their immobility has also made these species relatively easy to cultivate, thus permitting human enhancement of their populations.

The commercial production of all shellfish from Puget Sound was estimated to be 9,000 tons in 1983. By far the largest component of this yield is hardshell clams, accounting for about two-thirds of the tonnage. This is followed by oysters (which exceed the clam yield in dollar value), Dungeness crab, and shrimp. The trends in yield of each of these resources is discussed below.

Oysters

Commercial Pacific oyster planting and harvesting have been fairly stable over time (Figure 36). Seed oysters are raised in Puget Sound and imported from outside waters and are transplanted in commercial beds to develop. Some productive areas in Puget Sound have been taken out of production due to fecal coliform bacteria in the water and other forms of pollution. Increasing yields in the 1980-1984 period may have resulted from controlled laboratory setting of spat. Very recent research in genetics may increase marketability of oysters during summer months when they are normally of low quality. The necessity of clean water for future growth of the oyster industry cannot be overstated.

Commercial production of native (Olympia) oysters decreased rapidly from 1935 to the present. Pollution in south Puget Sound from pulp mill wastes is thought to have played a major role in the decline. Further impacts from overharvest and predation (from flatworms and drills which where introduced with oyster seed from Japan) nearly caused the oyster to become extinct. Good natural sets of the oyster in 1985 and a favorable market have encouraged several growers in the south Sound to develop large aquaculture operations, thereby assisting the oyster's comeback.

Hardshell Clams

Hardshell clam fisheries consist primarily of manila and native littleneck clams. In the 1930s and 1940s hardshell production was exclusively native littlenecks. Manilas were imported into the state's water along with oyster seed from Japan in the mid-1930s. Conditions in Puget Sound are similar enough to those in the manila clam's native Japan that they began populating intertidal beaches in the south Sound in the 1950s. Manila clams are now by far the most important commercial hardshell clam in the steamer clam market. Commercial

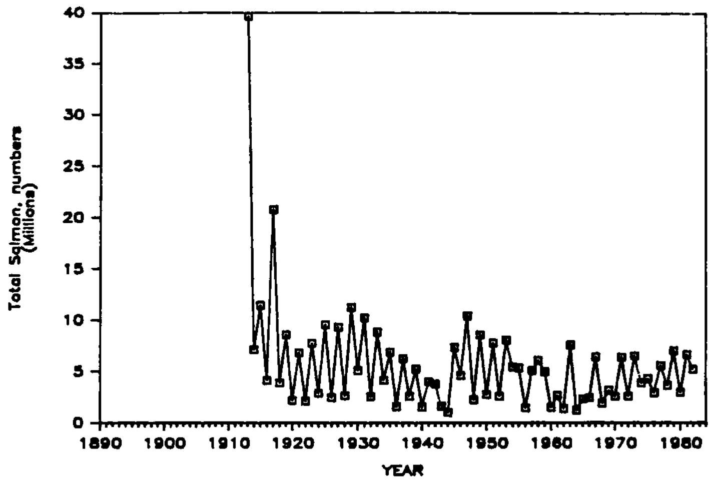


Figure 32

COMMERCIAL LANDINGS OF SALMON IN PUGET SOUND (1913-1982)

SOURCE:
Ward et al., 1974;
Ward and Hoines, 1982

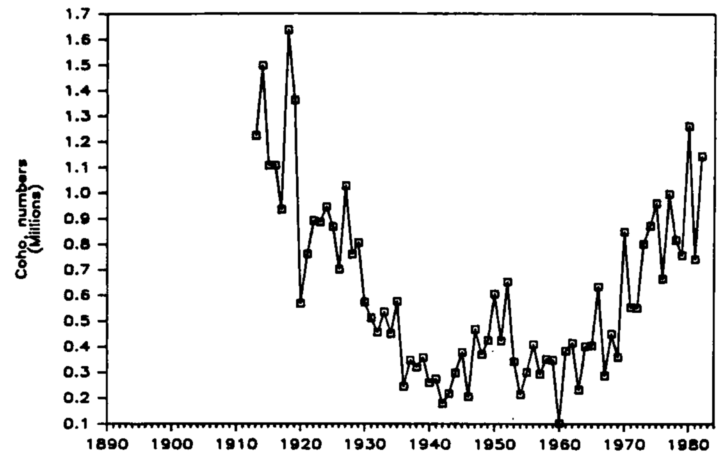


Figure 33

COMMERCIAL LANDINGS OF COHO IN PUGET SOUND (1913-1982)

SOURCE:
WDF, 1974; Ward et al., 1974;
Ward and Hoines, 1982

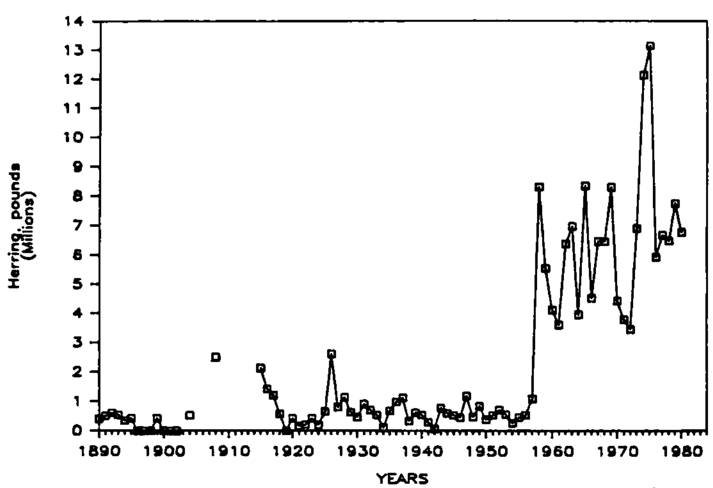


Figure 34

COMMERCIAL CATCH OF HERRING IN PUGET SOUND (1890-1982)

SOURCE:
WDF, Unpublished Data;
Quinnell, 1984

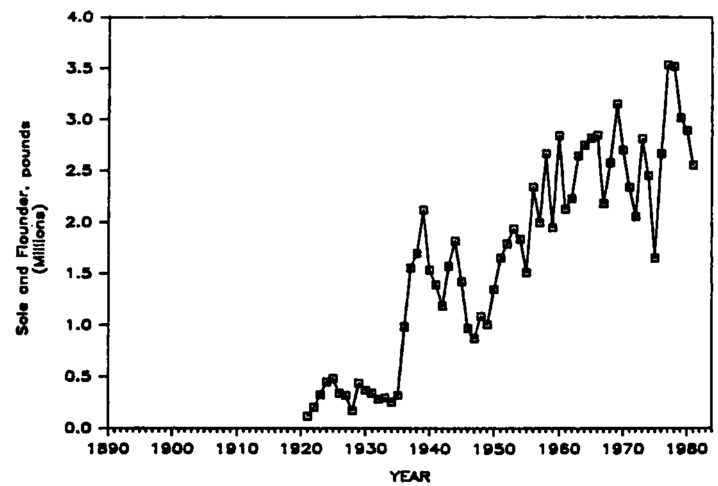


Figure 35

COMMERCIAL LANDINGS OF SOLE AND FLOUNDER IN PUGET SOUND (1921-1982)

SOURCE:
WDF, 1974; Ward et al., 1974;
Quinnell, 1984

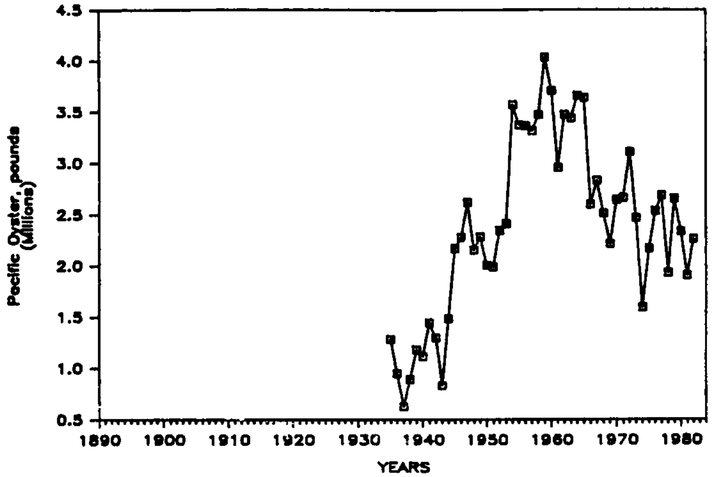


Figure 36

PRODUCTION OF PACIFIC OYSTERS IN PUGET SOUND (1935–1982)

SOURCE:
Ward et al., 1974;
Ward and Hoines, 1982

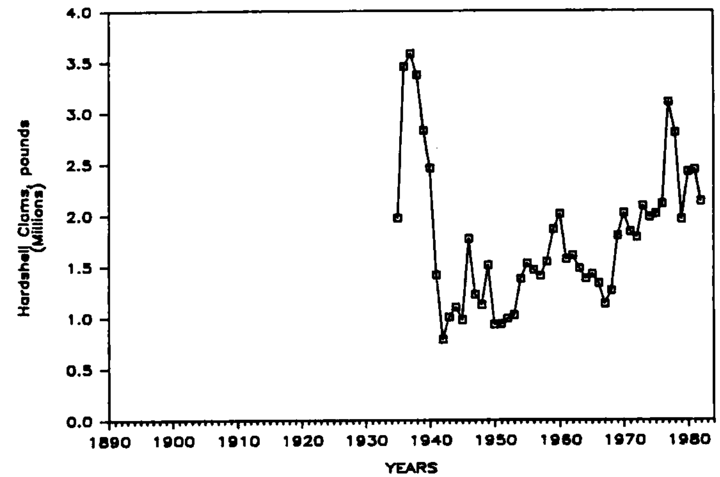


Figure 37

COMMERCIAL LANDINGS OF HARDSHELL CLAMS IN PUGET SOUND (1935–PRESENT)

SOURCE:
Ward et al., 1974;
Ward and Hoines, 1982

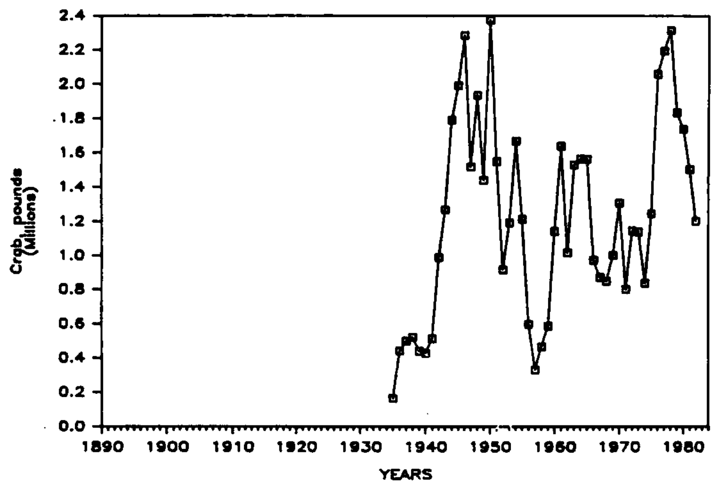


Figure 38

COMMERCIAL LANDINGS OF CRABS IN PUGET SOUND (1935–1982)

SOURCE:
Ward et al., 1974;
Ward and Hoines, 1982

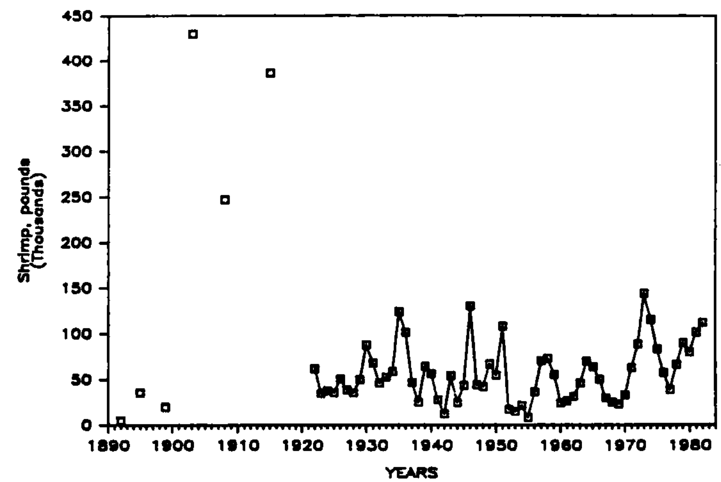


Figure 39

COMMERCIAL LANDINGS OF SHRIMP IN PUGET SOUND (1898–1982)

SOURCE:
WDF, 1937b; Ward et al., 1974;
Ward and Hoines, 1982

hardshell clam harvests are shown in Figure 37. The recreational clam harvest, estimated at over 1,500 tons in 1985, nearly equals the commercial harvest.

Other Molluscan Shellfish

Harvest of extensive subtidal beds of geoducks is regulated by the Washington State Department of Fisheries. Production is limited to a harvest of 2,500 tons a year on subtidal tracts put up for bid by the Washington Department of Natural Resources. Scallops, blue mussels, and octopus are also harvested.

Crustacean Shellfish

Puget Sound crab (Figure 38) and shrimp (Figure 39) are important commercially and recreationally. Most shrimp production comes from south Hood Canal. Crab and shrimp populations tend toward cyclic changes in abundance with large harvests occurring every two to six years. Regulation has led to an increased size of shrimp and a generally more stable resource.

RECREATION AND AESTHETIC ENJOYMENT

The marine waters of the Puget Sound basin represent an invaluable aesthetic and recreational resource for residents and tourists. People have a strong desire to live near the water. Fifty-five percent of the state's residents reached in a recent poll (conducted for the Puget Sound Water Quality Authority this year) live within one-half mile of a body of water. And 36 percent of polled residents of the Puget Sound region live within one-half mile of saltwater. The value of living on saltwater is reflected in the high property values of shoreline residences.

The recreational use of the marine waters is also dramatic. Seventy-three percent of area residents and 56 percent of residents statewide have been on the saltwater or beaches of the Puget Sound basin in the past year.

The state Comprehensive Outdoor Recreation Plan includes information on the frequency with which Washington residents engage in various outdoor recreational activities (Table 10). One-third of outdoor recreational activities involve fresh or saltwater.

Recent estimates indicate that resident travelers spend $1.4 billion and create 40,000 jobs statewide. About two-thirds of these expenditures were made in counties bordering Puget Sound. This figure suggests that about 27,000 jobs in the Puget Sound region may depend on travel expenditures by Washington residents.

A recent survey of out-of-state tourists in Washington State identified its waterways as a primary attraction (only the mountains were more popular), followed closely by seafood and outdoor recreation. This combination of attractions leads to very large number of tourist visits and expenditures. An estimated 22.8 million visitor-days yielded expenditures of $857.6 million in 1984 and created an estimated 24,000 jobs. Seventy-five percent of these tourist expenditures were made in counties bordering Puget Sound. About 18,000 jobs in the Puget Sound region are supported by non-resident tourist expenditures. Although the contribution of saltwater recreation to these totals is not analyzed, it is clearly very important to the economy of the region. Businesses most dependent on these tourist expenditures include: accommodations and campgrounds; eating and drinking establishments; gas stations,

parking, vehicle rental and other transportation services; retail and grocery stores; and recreation firms. A study of the maritime recreation industry in Washington State estimated sales (for the year 1977) at over $500 million and jobs dependent on these expenditures at over 14,000.

The type and magnitude of human use of the Puget Sound basin has clearly changed in the last 150 years. Puget Sound is also exceedingly valuable as a resource. The next chapter presents information on the effects of human activities on the Sound.

TABLE 10: OUTDOOR RECREATIONAL ACTIVITIES BY WASHINGTON RESIDENTS

		Activity Occasions *(in millions)*
Bicycling for Pleasure		27.86
Day Hiking		14.71
Picnicking		18.27
Boating:	Power	10.57
	Other	5.59
	Fishing	17.93
	Waterskiing	4.48
Camping:	Vehicular	21.97
	Other	6.31
Swimming at a Beach		12.12
Driving for Pleasure		23.85
Fishing from Shore		5.54
Hunting		4.01
Food Gathering		4.17
Nature Study		3.76
Visiting the Beach, Beachcombing		2.97
Crabbing, Clamming, Oyster Gathering		1.74
Walking for Pleasure		5.29
	TOTAL	191.14

(Source: SCORP, 1985)

PUGET SOUND TIMELINE

BEFORE 1845: THE NATIVE AMERICAN PERIOD

By 8000 BC	Native Americans reside in the basin.
1700	Native American civilization well established in the basin.
1792	Captain Vancouver explores and names Puget Sound.
1833	Fort Nisqually established as first trading post on Puget Sound.

1845-1880: NON-INDIAN SETTLEMENT

1845	First permanent non-Indian settlement at Tumwater.
1851	California Gold Rush construction boom reaches Puget Sound
1853	Washington Territory established.
	First steam sawmill built in Seattle by Henry Yesler.
1854-55	Puget Sound Indian treaties.
1872	San Juan Island dispute with Great Britain settled in favor of the United States.

1880-1940: THE BIG BOOM

1883	Transcontinental railroad connects Tacoma with East Coast.
1889	Washington statehood.
1891	Puget Sound Naval Shipyard established at Bremerton.
1897	Klondike Gold Rush begins.
1899	Mt. Rainier National Park established.
1910s	Large losses of wetlands for agriculture and industrial development.
1910	Tacoma approves municipal dock facilities.
1911	Port of Seattle established.
1913	Commercial harvest of salmon on Puget Sound peaks.
1914	World Ward I begins.
1916	First Boeing airplanes built.
1917	Lake Washington Ship Canal opens.
1920s	Adverse effects of pulp industry on Puget Sound.
1930s	Communities around Lake Washington begin sewage treatment.
	The Great Depression.
1937	U.S. and Canada treaty for joint management of Fraser River sockeye salmon.

1940-1970: TRANSITION TO THE MODERN ECONOMY

1940	Original Tacoma Narrows Bridge collapses.
1942	US enters World War II.
1945	State establishes Water Pollution Control Commission.
1948	First Federal Water Pollution Control Act passed.
1950s	Bridges built: Hood Canal, Agate Pass, and Tacoma Narrows.
	First oil refinery on Puget Sound.
1958	Metro formed to construct and operate regional sewage treatment system.
1966	West Point treatment plant begins operation.
1968	Formation of the Washington Environmental Council.
1969	Boeing layoffs begin.

1970-1985: RECENT TIMES

1971	Passage of the Shorelines Management Act.
	Passage of the State Environmental Policy Act.
1972	Passage of the federal Clean Water Act
1974	Boldt decision in federal court affirming Indian treaty fishing rights.
1981	Trident submarine facilities completed at Bangor.
1982	Northern Tier Pipeline project dies.
1985	Puget Sound Salmon Management Plan adopted.
	U.S. and Canada sign Salmon Management Treaty.
	Puget Sound Water Quality Authority established.

III. Contamination of the Puget Sound Basin

INTRODUCTION

The subject of this chapter is the contamination of the water, sediments, and organisms of Puget Sound: its nature, causes, history, distribution, and consequences for the health of living resources and for the health of humans using those resources.

Contamination is usually expressed in terms of concentration--that is, the quantity of contaminant in a given amount of air water, sediment, or animal tissue. For example, the amount of contaminant in a sample of water, sediment, or tissue can be expressed as a fraction of the sample's total weight (or volume). Because of the range of concentrations that exist and are measurable with modern equipment, and because of the ability of some substances to cause biological harm when present in tiny amounts, the magnitude of such fractions ranges from percentages (parts per hundred) to parts per million (ppm) and parts per billion (ppb). For example, seawater from Puget Sound commonly has 30 pounds of salt in each 1,000 pounds of pure water. In a bathtubful of seawater (about 60 gallons) there would be about 15 pounds of salt. If, instead of 15 pounds of salt, one teaspoon of salt is placed in the same amount of water, the resulting concentration would be about 30 parts per million. A concentration of 30 parts per billion would result from adding less than a single grain of salt. One part per billion is equivalent to five people out of the total population of the earth. Although concentrations of parts per billion may seem insignificant, certain compounds can be harmful to organisms at these concentrations.

CLASSES OF CONTAMINANTS

Society produces, uses, and disposes of such a tremendous variety of materials--many of which come into contact with Puget Sound--that it is impossible to discuss each in detail. However, an overview of contaminants affecting the Sound can be grouped into categories based on common properties.

Organic Chemicals

These are some of the most-discussed contaminants in the Sound but some of the least understood. Organic chemicals are, in general, those that contain carbon. Within this definition is an almost infinite variety of natural and synthetic (man-made) compounds.

The list of natural organic chemicals includes most of the building blocks of our bodies and our foods (fats, proteins, and carbohydrates) as well as plant and animal products such as wood, leather, cotton, and wool. Some natural organic matter has been altered over millions of years to form fossil fuels (coal, oil, and gas).

In the last few decades the list of synthetic organic chemicals has lengthened with the continued addition of new plastics, synthetic rubbers, pesticides, herbicides, and other substances. Many synthetic organic chemicals are known for their resistance to decomposition or breakdown (called persistence) and

their toxicity to living organisms. Some of the most persistent and toxic of the synthetic organic chemicals contain the elements chlorine and bromine, members of a group of elements called halogens. Compounds combining halogens in organic chemicals are called halogenated hydrocarbons. Many of these chemicals are produced and used precisely because they are persistent and toxic. For example, many pesticides and herbicides are halogenated hydrocarbons. The PCBs are a family of toxic halogenated hydrocarbons produced as coolants and insulators for electrical components. New synthetic compounds continue to be created and introduced into society and, ultimately, into wastewater discharges.

Organic materials also damage the environment by providing food for bacteria which break down synthetic organic chemicals and any living matter that has died. The food for these bacteria can include anything from natural remains of algae and fish to sewage or pulp mill waste. Bacterial decay is nature's way of avoiding a buildup of dead material in seawater. It can cause a problem when it occurs on such a large scale that the bacteria consume dissolved oxygen from the water and other organisms die of asphyxiation. In technical terms, the amount of oxygen in a water body used up by bacteria as they decompose organic matter is called the biological oxygen demand (BOD). Fish kills caused by oxygen depletion (excess BOD) were not uncommon in parts of Puget Sound before cleanup measures were applied to discharges from sewage and pulp mills.

Inorganic Chemicals

The rest of the chemical world (anything not containing carbon) is called inorganic. The inorganic chemicals that are most relevant to contamination in Puget Sound include the heavy metals such as copper, lead, zinc, chromium, cadmium, arsenic, and mercury. Low concentrations of metals are present naturally in seawater, washed there by erosion of rocks and soils on land. Also among the inorganic chemicals are some simple compounds that act as nutrients for marine plants. The primary inorganic nutrients are compounds of nitrogen (nitrates and ammonium) and phosphorus (phosphates), two of the main constituents of fertilizers. Other examples of inorganic contaminants include acids used in pulp-and-paper processing and alkali found in home and industrial cleaning compounds (e.g., drain cleaner).

It can be difficult to determine when to categorize some inorganic chemicals as contaminants. Virtually all of them occur naturally in seawater, and several (especially the nutrients) are essential for life, but all can be harmful when present in large enough quantities or at the wrong place or time. Copper, for example, is essential to life in very minute quantities but is toxic at higher concentrations. The toxicity of metals also depends on their chemical form. Also, excess nutrients can cause overgrowths of algae which can rob the water of life-giving oxygen when they die and decay, causing fish kills and putrid odors. Since these substances are damaging in excess amounts, any additions to the system by human activities are problematical. Metals, in particular, are not used up in the environment but can only be diluted or buried.

Biological Contaminants

Harmful organisms are introduced into Puget Sound by municipal sewage treatment, septic systems, discharges from boats, and runoff from farms, forests, and cities. Notable among these organisms are bacteria and viruses, especially the pathogens that can cause diseases such as typhoid, cholera, salmonella, and hepatitis in humans. To protect people from potentially dangerous levels of microorganisms in the Sound, health officials close contaminated beaches to swimming and shellfish gathering. Shellfish are good indicators of microbial contamination for the same reason that such contamination makes them unsafe to eat--because they take up and concentrate microorganisms in large quantities through filter-feeding. Out of perhaps thousands of species of microbes that may be introduced into the Sound by human activities, only certain species--the fecal coliforms, which originate in the intestinal tract of warm-blooded animals, including humans--are monitored in shellfish. Fecal coliforms are indicators of fecal contamination and, although they are not pathogens (disease-causing) themselves, they indicate that pathogens may be present.

Paralytic Shellfish Poisoning

Paralytic shellfish poisoning, commonly known as PSP, is a serious human illness caused by eating bivalves (clams, mussels, oysters, and scallops) that have ingested large amounts of a particular species of phytoplankton. That species is one of several that can generate "red tides" in Puget Sound (most of which are not red) but is the only one known to be toxic. Extremely potent neurotoxins produced by the phytoplankton organism, Gonyaulax, accumulate in bivalves' tissues. Although these toxins apparently cause no harm to the bivalves, they are very toxic to mammals including humans. When enough of these toxins are consumed, human death from respiratory paralysis can occur within 24 hours. No antidote has yet been discovered.

Shellfish are more likely to become hazardous to humans in late spring, summer, and fall. At these times the PSP organism is more abundant in surface waters and more available to be filtered by shellfish. However, the PSP organism can also form non-swimming cells (cysts) which settle to the bottom sediments. If large numbers of these cysts occur in the sediment, shellfish may consume them at any time of year and become poisonous.

The Washington State Department of Social and Health Services, and health departments of counties bordering Puget Sound, test recreationally and commercially harvested shellfish for PSP toxins. When toxin levels are too high, beaches are posted as temporarily closed to both commercial and recreational harvesting.

Contaminant Mixtures

Some of the contaminants discussed above enter the Sound in complex mixtures. The effluent from sewage treatment plants, for example, contains virtually every contaminant that ever reaches the Sound including oils, metals, pesticides, and nutrients. Human waste, in addition to containing pathogenic microorganisms, is a rich source of nutrients that stimulates plant growth. Sewers are the catchall disposal mechanism for society, and nearly anything used by people shows up there and eventually reaches the Sound.

Other effluents also contain mixtures of contaminants. For example, surface runoff from urbanized areas contains mixtures of contaminants as diverse as oil

and rubber from automobiles, fertilizers and pesticides from lawns, and garbage from streets and alleys. Industrial effluents often contain mixtures of toxic wastes that vary in composition according to the particular process that produced them.

Sediments and Other Particles

Particles in the water and sediment are also extremely important in the inventory of potential contaminants. Particles enter the Sound naturally from shorelines and rivers and are generated by the growth of plants and animals. They contain both inorganic chemicals eroded from rock and organic chemicals extracted from soil and derived from organisms. Human activities add to the natural influx of particles. For example, earthmoving and clearcutting of forests increase the erosion rate from shorelines and river banks; dredging stirs up clean and dirty particles from the bottom of the Sound and redistributes them; and contaminant-laden particles are added to the Sound in sewage effluent. Too much sediment can cloud the water, limiting light to plants and smothering animals or damaging their gills and other sensitive tissues. Furthermore, suspended particles tend to remove certain contaminants from the water and concentrate them on their surfaces. Smaller particles are particularly efficient at this process. Thus, the sediments of the Sound not only can be harmful in themselves, but also can act as vectors for the transport of contaminants. The estuarine circulation of the Puget Sound basin retains most particles and the contaminants bound to them in the basin, preventing their transport to the ocean.

SOURCES OF CONTAMINANTS

The sources of contaminants reaching Puget Sound are varied. Each contaminant can reach the Sound by several different routes, and each type of source can carry many different contaminants. As a matter of practicality, types of contaminant sources are divided into two broad categories: point and nonpoint sources.

POINT SOURCES

A point source is one that delivers contaminants to the water through a single method of conveyance such as a pipe, trough, or slough, even if that pipe carries an accumulation of waste products from a broad area and from many different original sources. That is, the waste pipe from a single factory is a point source, and so is the effluent pipe from a sewage treatment plant that collects the waste from many square miles of homes, factories, businesses, roads, and parks. Combined sewer overflows and storm drain pipes can also be considered point sources, although contamination in stormwater is normally caused by nonpoint sources such as oil from parking lots or spilled products washed from industrial yards. Combined sewer overflows are simply raw, untreated discharges from sewer systems caused by excess flow during rainstorms.

Two major categories of point sources are industrial waste discharges and municipal sewage outfalls. Under the National Pollution Discharge Elimination System (NPDES) of the Clean Water Act, both are required to obtain discharge permits. In Washington State, the Department of Ecology administers the

NPDES permit process. The permits generally specify maximum amounts of contaminants that can be discharged. Contaminants addressed in a given permit may include bacteria, suspended solids, biological oxygen demand (BOD), some metals, and, occasionally, some organic toxicants. Permit holders are required to monitor certain characteristics of their discharges.

Storm drain systems are only now being required to apply for NPDES permits and are not today subject to numeric discharge limits.

Every other source is called a nonpoint source. The main distinction is that nonpoint sources do not have a single discharge point. Many of the same processes that contribute to point source contamination also contribute to nonpoint source contamination but do not pass through single pipes. Land runoff from cities, farms, and forests and subsurface runoff from landfills and septic tanks are some principal nonpoint sources.

Although more needs to be done, point sources are subject to significant requirements for treatment. It is difficult to imagine the condition of the Sound without the limits currently placed on point sources. Historic information presented below indicates that large parts of the marine waters of the basin would be significantly degraded. By comparison, there is very little control of nonpoint sources.

NONPOINT SOURCES

Because of the dispersed nature of nonpoint sources, there are few exact estimates of their number or of how much contamination they contribute to the Sound. Yet, as will be discussed, nonpoint sources are known to cause problems in specific cases. Nonpoint sources are found virtually everywhere there are people. In essence, everyone contributes to nonpoint source contamination whether they are aware of it or not.

Individuals generate contamination by consuming and discarding products containing contaminants. A large portion of the contaminants in municipal sewage, for example, originates from the use and disposal of household products such lawn and garden herbicides and pesticides, paint and paint thinner, gasoline and oil, solvents and cleaning agents, shampoos, and cooking grease. These materials may be poured down sinks or sewers or may be carried passively by surface runoff of precipitation to streams and sewers.

Surface runoff from rural, suburban, and urban areas is a significant contributor to human contamination which affects the environment. Rainfall and melting snow wash contaminants into lakes, streams, and rivers, and, eventually, into the Sound.

Surface runoff in suburban and urban areas carries contaminants into storm drains. Many cities and municipalities collect urban stormwater in the same system of pipes that are used to collect sewage. Under dry or slightly rainy conditions, all of the water is treated at a sewage treatment plant before it is released into a river, stream, or the Sound. However, under very high flow conditions such as those following a heavy rainstorm, the combined flow of sewage and stormwater may exceed the capacity of the pipes and treatment plant, and a portion of the untreated flow will spill directly into a body of

water out of a combined sewer overflow (CSO). Raw sewage and untreated stormwater are released directly into the receiving water to avoid flooding and damage to pipes and treatment facilities. Older collection and treatment systems that were not designed to carry current waste volumes are most likely to overflow. Systems built in the last 20 years, particularly in newer urban areas, are more likely to have the necessary capacity to avoid overflows (except during extreme rainfall conditions) because they generally include separated sanitary and storm sewers. Unfortunately separated stormwater systems do not provide any treatment before the stormwater is discharged.

DREDGED MATERIAL

Dredge spoil disposal is another source of contamination that is restricted to certain locations and yet is not strictly considered a point source. Dredging is carried out in river mouths and harbors by the U.S. Army Corps of Engineers and port districts to deepen channels for new harbor facilities and to maintain old ones that fill in with silt. Open water dumping of dredge spoils can block sunlight to aquatic plants, foul the gills of animals, and bury benthic organisms. In addition, disposal of sediments dredged from contaminated sites such as urban bays can spread contamination to relatively uncontaminated areas. Sites for disposal of dredge spoils in Puget Sound (Figure 40) are administered by the Washington State Department of Natural Resources. Significant changes in the dredged material disposal system have occurred in the past five years and a major interagency study is underway to improve it further. Seriously contaminated sediments cannot now be disposed of in the Sound.

SUMMARY OF SOURCES

Figure 41 depicts schematically some of the major nonpoint and point sources of contamination. The following listing of nonpoint and point sources corresponds to that figure.

1. Atmospheric sources include lead and hydrocarbon exhausts from automobiles, and gases and particles from factory and power plant chimneys which enter the water directly or are carried by runoff;

2. Forestry and logging contribute contaminants from soils eroded off roads and clearcuts, and from herbicides;

3. Runoff from commercial and domestic agriculture carries fertilizers, pesticides, particles eroded from soil and shorelines, and animal waste;

4. Runoff from suburban and rural residential areas carries wastes from lawns and gardens, pets, cars, septic tanks, and household paints and chemicals;

5. Landfills can contaminate surface water and groundwater with virtually every material used and disposed of in society;

6. Highways are significant sources of hydrocarbons, metals, and contaminated particles;

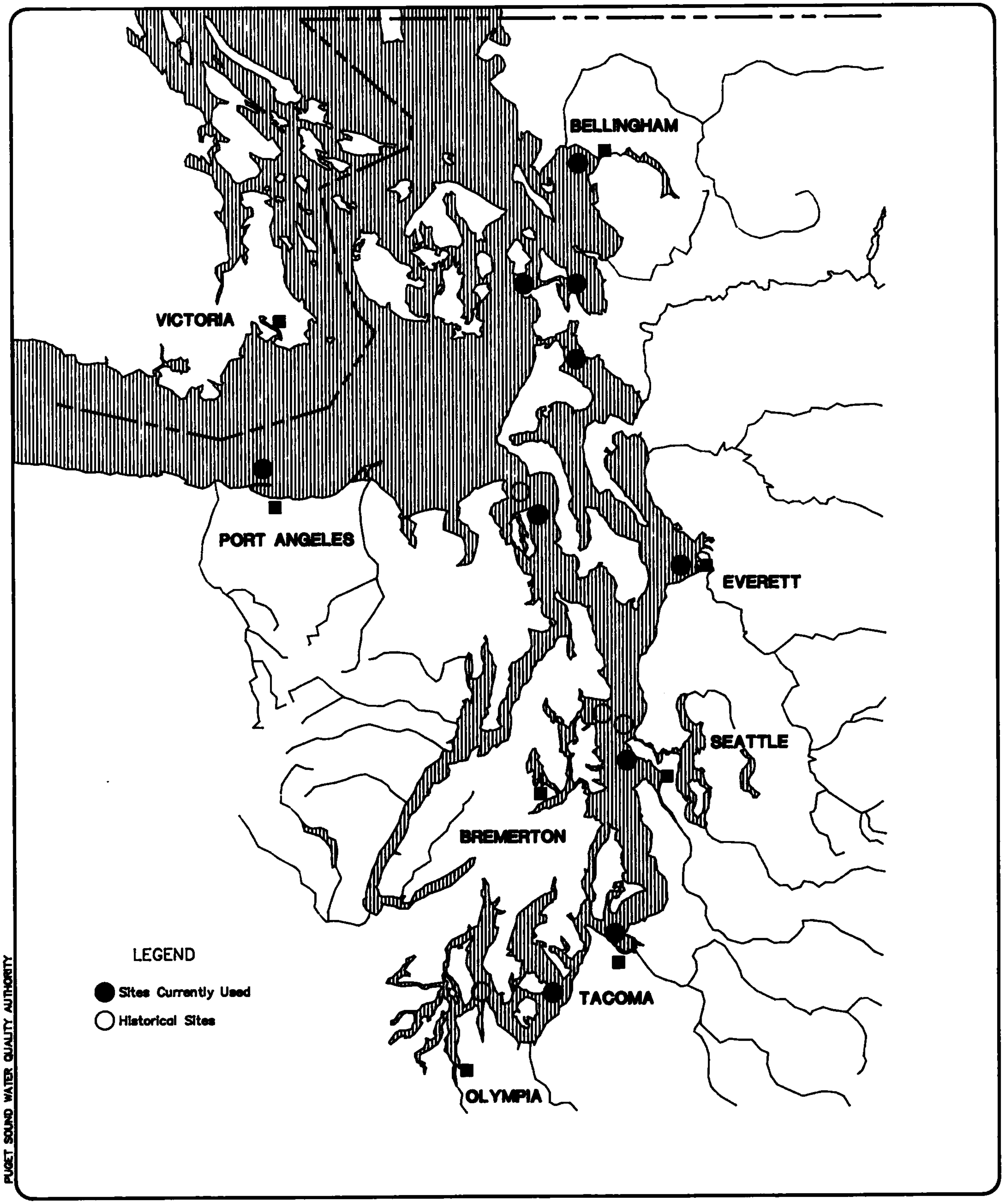


Figure 40

DREDGE SPOIL DISPOSAL SITES
IN PUGET SOUND

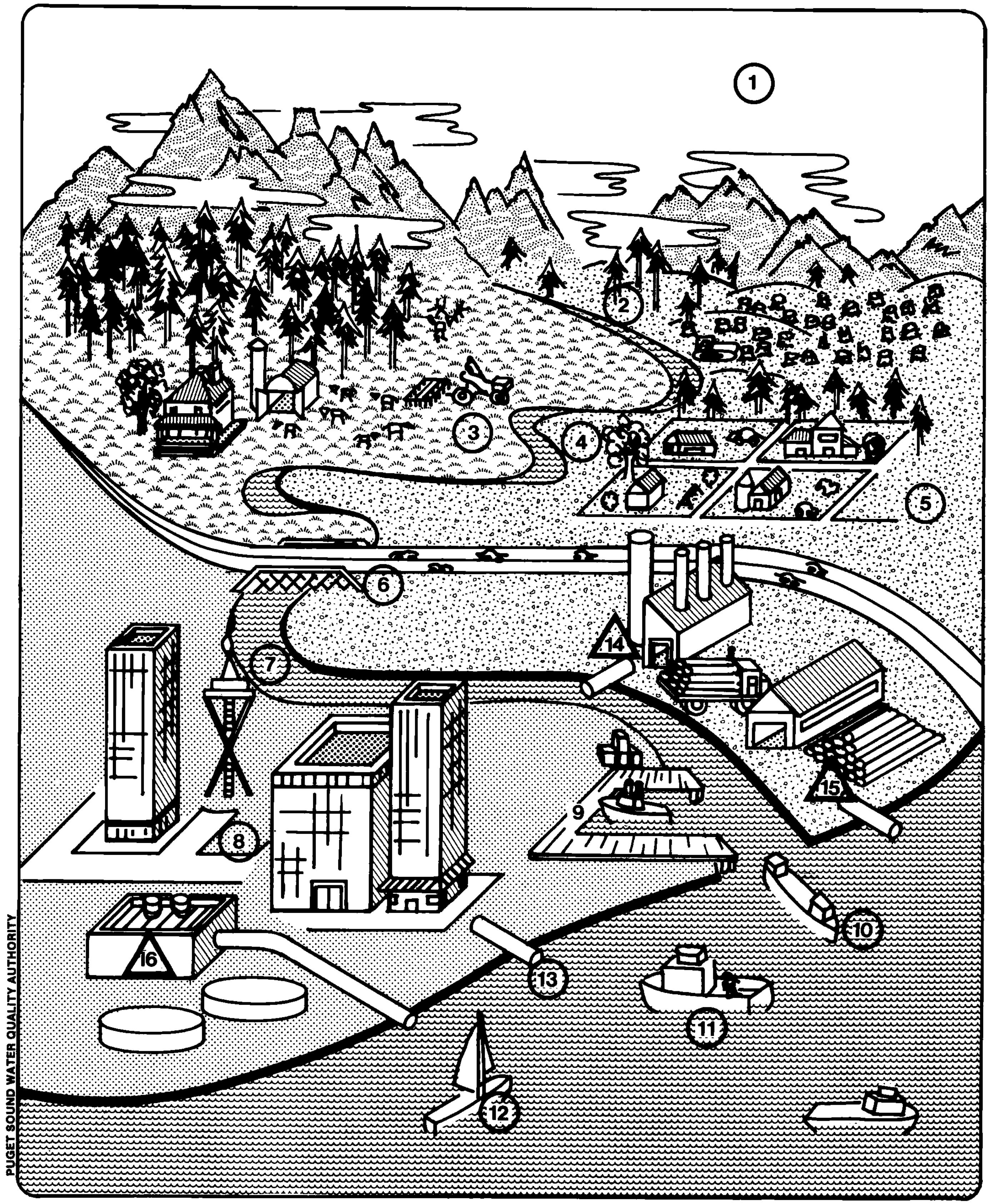


Figure 41

SOURCES OF CONTAMINANTS ENTERING PUGET SOUND

7. Rivers, though not the source of contaminants, carry them into the Sound. The contaminants enter the rivers as direct discharges or as runoff;

8. Surface runoff from urban areas contains contaminants from streets and motor traffic, commercial and industrial activities, and human and animal inhabitants;

9. Shipbuilding, drydocks, and other marine industries contribute metals, organic chemicals, and other ship-related debris;

10. Shipping can be a source of spillage or discharges of cargo, fuel, sewage, and refuse, and of metal contamination;

11. Dredging and dredge spoil disposal redistributes contaminated particles;

12. Recreational boating contributes fuel, sewage, and refuse spillage;

13. Combined sewer overflows (CSOs) combine surface stormwater runoff from urban and suburban areas with sewage and industrial wastewater and, during heavy precipitation, discharge some of it directly to the Sound without treatment;

14. Waterfront industries discharge a wide range of contaminants to rivers and the Sound;

15. Waterfront forest products industries, such as pulp and paper mills and log-shipping yards, discharge wastewaters to the Sound;

16. Municipal sewage treatment plants discharge large volumes of treated wastewater.

LOADING OF CONTAMINANTS

The amount of a contaminant that is released per year is called the loading of the contaminant. Loading is calculated by multiplying the concentration of the contaminant by the volume released. For example, if a river carries a contaminant at a concentration of one part per billion and that river flows at a rate of one cubic kilometer per year (about the flow of the Skagit River), the loading from that river is one ton of contaminant per year.

LOADINGS FROM POINT SOURCES WITH PERMITS

There are over 400 permitted point source discharges entering Puget Sound and its tributary rivers, 56 of which are considered to be "major" sources by EPA. These major discharges are mainly large municipal sewage treatment plants, although some industrial dischargers also fall into this category. Some of the largest major and minor discharges in Puget Sound are listed in Table 11; other discharges are noted on Figure 42. Minor discharges located on rivers and tributaries to the Sound are not shown on Figure 42; they make up the remainder of the 400 discharges. These discharges were chosen to give an idea of the geographic distribution and diversity of discharge types and volumes present in Puget Sound. The values in Table 12 are the discharges of

TABLE 11: SELECTED POINT SOURCE DISCHARGES TO PUGET SOUND

Source	Type of Discharge	Discharge to	Discharge Volume in Millions gal/yr	Suspended Solids in Thousands lbs/yr	Bacteria in Billions/yr
Mobil Oil Corp.	Petroleum Refining	Georgia Strait	--	91,000	--
City of Bellingham	Municipal Primary	Bellingham Bay	5,850	2,920	160,000
Georgia-Pacific Corp.	Pulp, Paper, Chemical	Bellingham Bay	20,500	12,300	--
City of Everett	Municipal Lagoon	Snohomish River	11,320	2,000	6,600
Scott Paper Co.	Pulp, Paper	Port Gardner Bay	12,000	9,200	--
Weyerhaeuser Co.	Pulp	Steamboat Slough	7,670	4,900	--
ITT Rayonier Inc.	Pulp	Port Angeles	4,400	15,000	--
ITT Rayonier Inc.	Dissolving Pulp	Port Angeles	11,800	--	--
Metro	Municipal Primary	Alki	5,475	1,830	153,000
Metro	Municipal Primary	West Point	71,180	38,000	2,000,000
Metro	Municipal Secondary	Green River	13,140	5,300	105,000
S.W. Suburban Sewer Dist.	Municipal Primary	Normandy Park	2,920	710	82,000
City of Bremerton	Municipal Primary	Sinclair Inlet	1,300	1,400	36,000
U.S. Navy	Stormwater	Sinclair Inlet	3,200	--	--
City of Olympia	Municipal Secondary	Budd Inlet	5,950	1,500	48,000
Boise Cascade Corp.	Pulp, Paper	Steilacoom	1,400	6,753	--
City of Puyallup	Municipal	Puyallup River	4,000	510	32,000
Occidental Chemical	Chemical Mfg.	Hylebos Waterway	8,900	280	--
Pennwalt Chemical	Chemical Mfg.	Hylebos Waterway	4,700	4,700	--
Simpson Timber	Kraft Pulp Mill	Commencement Bay	12,400	5,500	--
St. Regis Paper Co.	Pulp, Paper	City Waterway	13,900	4,400	--
City of Tacoma	Municipal Primary	Puyallup River	13,870	14,000	390,000
City of Tacoma	Municipal Primary	Commencement Bay	3,650	2,400	29,000

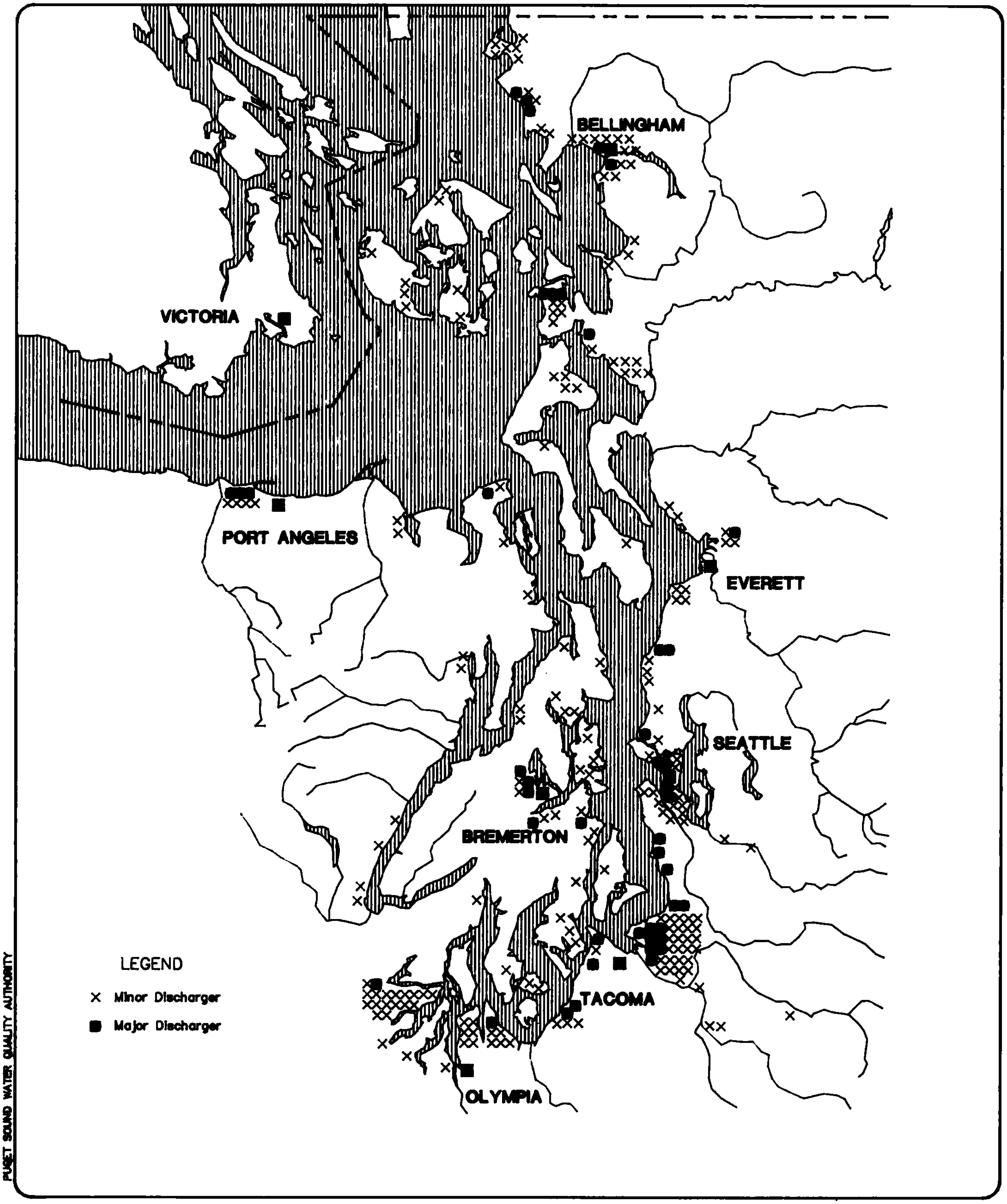


Figure 42

MAJOR AND MINOR POINT SOURCE DISCHARGES INTO PUGET SOUND

conventional contaminants allowed by permit, rather than actual measured loadings. There is no uniform monitoring of toxic compounds in these discharges.

Point source discharges are present in all areas of Puget Sound but tend to be clustered around the industrialized, urbanized areas including Seattle (a total of 16 discharges into Elliott Bay), Tacoma (36 into Commencement Bay), Shelton (10 discharges), and Olympia (nine into Budd Inlet). The total discharge of treated water and contaminants into Puget Sound can be roughly estimated from the data available. Table 12 summarizes this information for flow, solids, and bacteria for 234 of the major and minor discharges for which data are available.

Municipal sewage treatment plants also discharge toxic organic compounds and metals. The quantity of metals in the discharge is strongly influenced by the amount of industrial wastewater discharged to the system.

The loading figures from Table 12 do not indicate the degree to which these discharges can be concentrated in certain parts of the area. As an example, in Commencement Bay 36 existing pipes are permitted to discharge 64 billion gallons (241 million cubic meters) of effluent each year, containing 14,500 tons (32 million pounds) of solid matter and 419 trillion fecal coliform bacteria as well as other dissolved and suspended contaminants not covered in the permits. Based on the summary of loading in Table 12, this amounts to approximately 20 percent of the total point source flow into all of Puget Sound, 13 percent of all the solids, and 12 percent of all the fecal bacteria--all in one small corner of the Sound.

TABLE 12: TOTAL POINT SOURCE LOADING FOR MAJOR AND MINOR DISCHARGES IN PUGET SOUND

Parameter	Annual Loading
Flow (millions of gallons)	319,065
Solids (thousands of pounds)	253,296
Fecal Coliforms (billions of bacteria)	3,414,370

(Source: EPA Technical Law Report, 1985)

Combined sewer overflows may be major contributors to water quality problems in certain localized areas of Puget Sound. At least nine cities have CSOs that discharge into the Sound (Table 13), but there are flow monitoring data only for the Metro/City of Seattle CSOs, which account for over 60 percent of all the CSOs. Assuming normal rainfall in the Puget Sound region and proper and efficient running of the system, METRO estimates that 1.7 billion gallons of untreated sewage flows into the lower Duwamish River and Elliott Bay in a year. Sediment hot spots have been identified off of CSO outfalls in Elliott Bay.

TABLE 13: PUGET SOUND CITIES WITH COMBINED STORM AND WASTEWATER SEWERS

City	Receiving Water
Anacortes	Guemes Channel and Fidalgo Bay
Bellingham	Bellingham Bay
Blaine	Drayton Harbor (Strait of Georgia)
Bremerton	Sinclair Inlet
Everett	Port Gardner
Marysville	Possession Sound
Olympia	Budd Inlet
Port Angeles	Port Angeles Harbor (Strait of Juan de Fuca)
Seattle (Metro)	Elliott Bay and Main Bain of Puget Sound

(Source: EPA Technical Law Report, 1985)

LOADINGS BY NONPOINT SOURCES

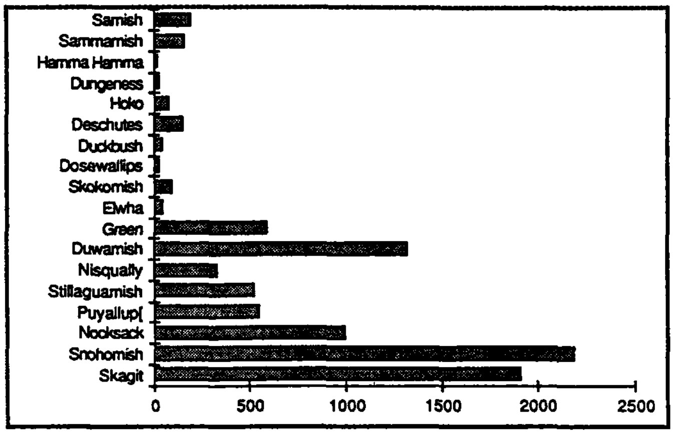
Information on water flow and water quality is available for a limited number of rivers and streams and has been used to develop rough estimates of the amount of certain contaminants (inorganic phosphorus and nitrogen, and fecal coliforms) that these streams and rivers carry into Puget Sound each year (Figure 43). Much of this contamination originates from nonpoint sources although point sources are also present on some rivers. For example, according to the data, the largest contributor of inorganic nitrogen to the Sound is the Snohomish River which transports more than 2,000 metric tons (4.4 million pounds) annually. This system also contributes over seven quadrillion fecal coliform bacteria per year (Figure 43). There are too few data on toxic contaminants in rivers to allow quantitative estimates.

The contaminants in the wastewater from an industrial or commercial process (e.g., copper smelting or photo finishing) are specific to that process. By comparison, loadings from nonpoint sources and storm drain systems can be estimated based on the relationship between land uses and the characteristic contaminant loadings associated with those land uses. A few small-scale studies have been done that give this type of information.

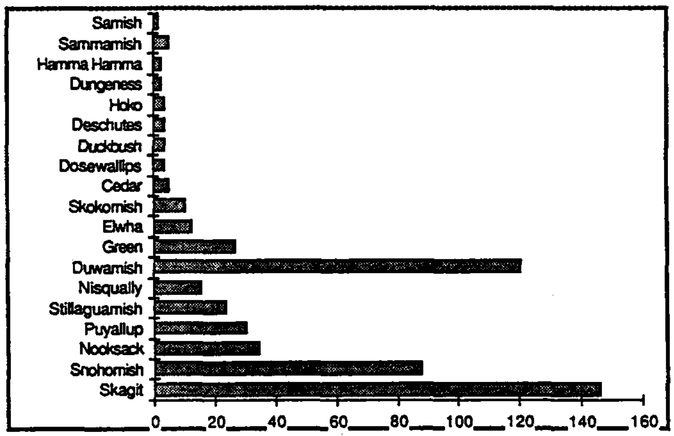
The examples used here include the Newaukum, Bear/Evans, and Big Beef Creek watersheds which are predominantly agricultural, urban/suburban, and forested, respectively; and the Burley/Minter and Eld/Henderson watersheds which are mainly rural/residential.

Agricultural Land Use

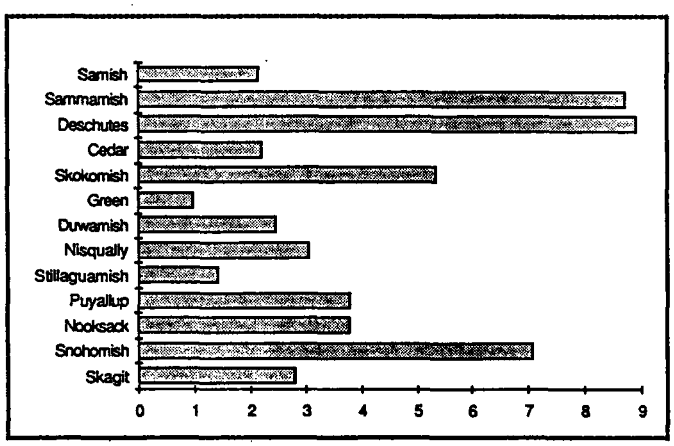
Agricultural land uses (cropland and rangeland) cover from four to 25 percent of the nine Puget Sound basins (Figure 44). Typical agricultural practices that have been linked to nonpoint contamination and water quality problems include poor waste management in livestock confinement areas, land application of manure, and livestock access to streams. The Newaukum Creek watershed in south-central King County (Figure 45) is predominantly agricultural. It drains 69 square kilometers (27 square miles) and consists of 56 percent agricultural land, 37 percent forested land, and seven percent urban land. Contaminant concentrations in and flows of stormwater runoff (Figure 46) were measured



METRIC TONS
NITROGEN LOADING



METRIC TONS
PHOSPHORUS LOADING



TRILLION ORGANISMS
FECAL COLIFORM LOADING

Figure 43

ANNUAL CONTAMINANT LOADING TO PUGET SOUND BY MAJOR RIVERS

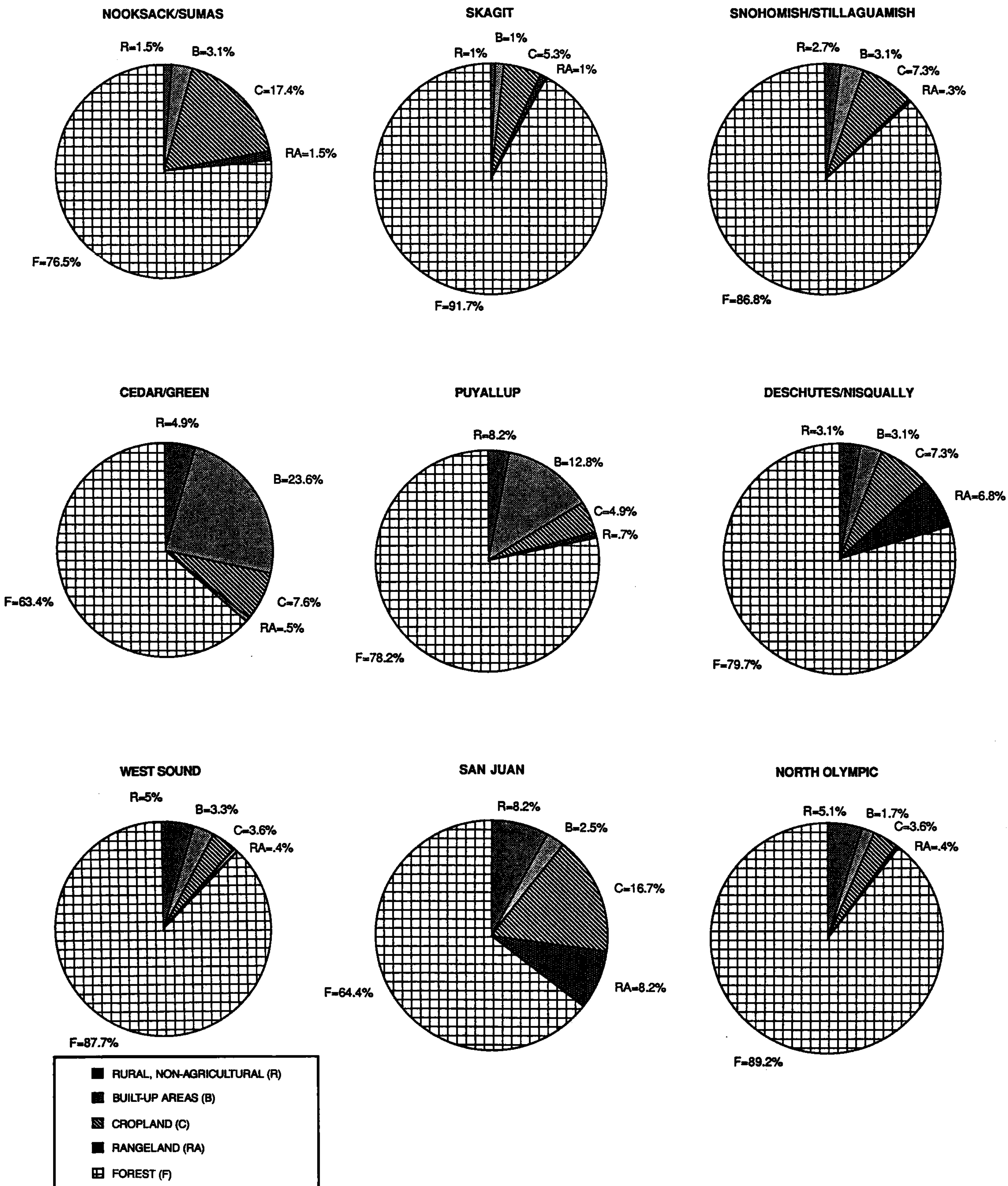
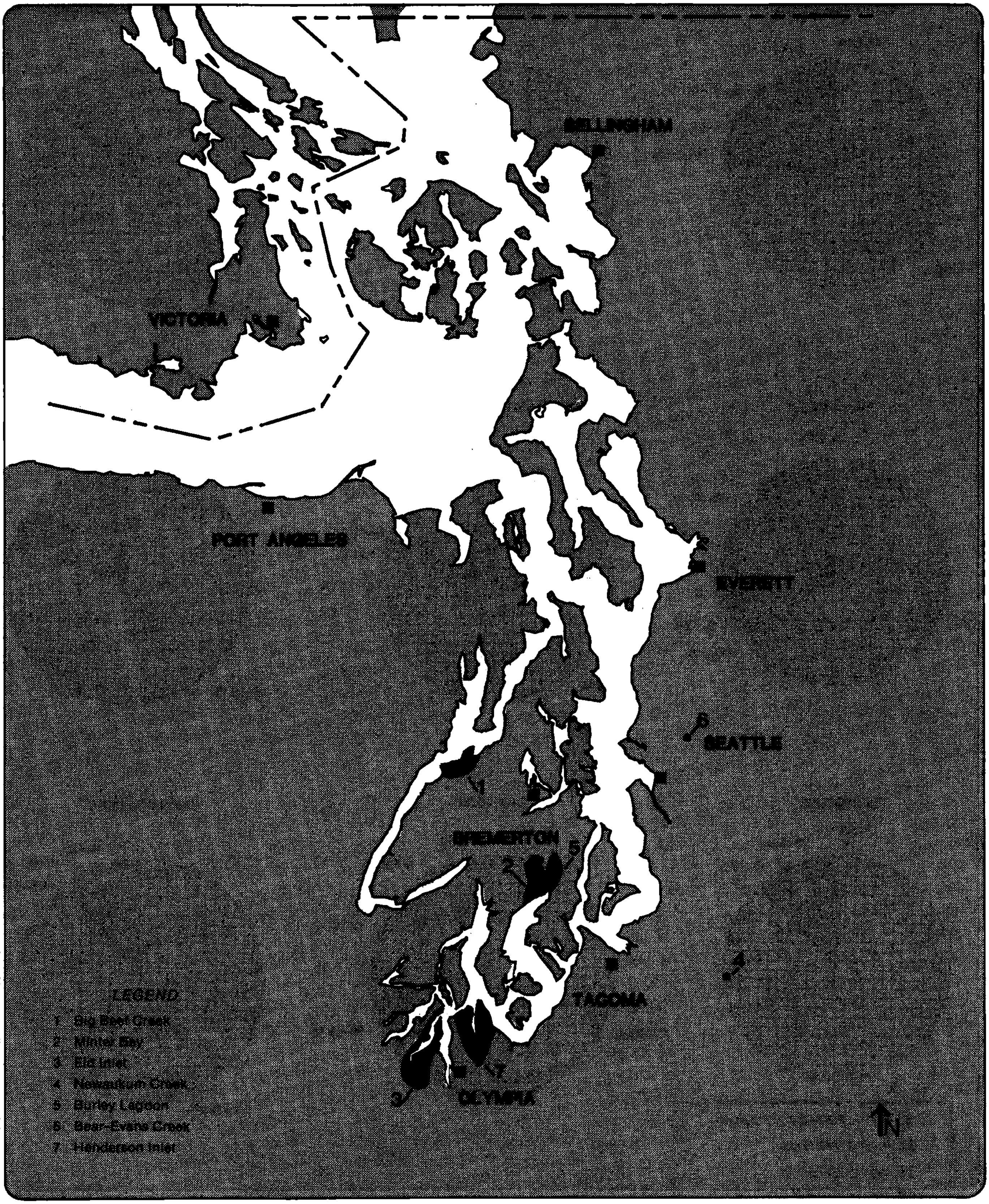


Figure 44

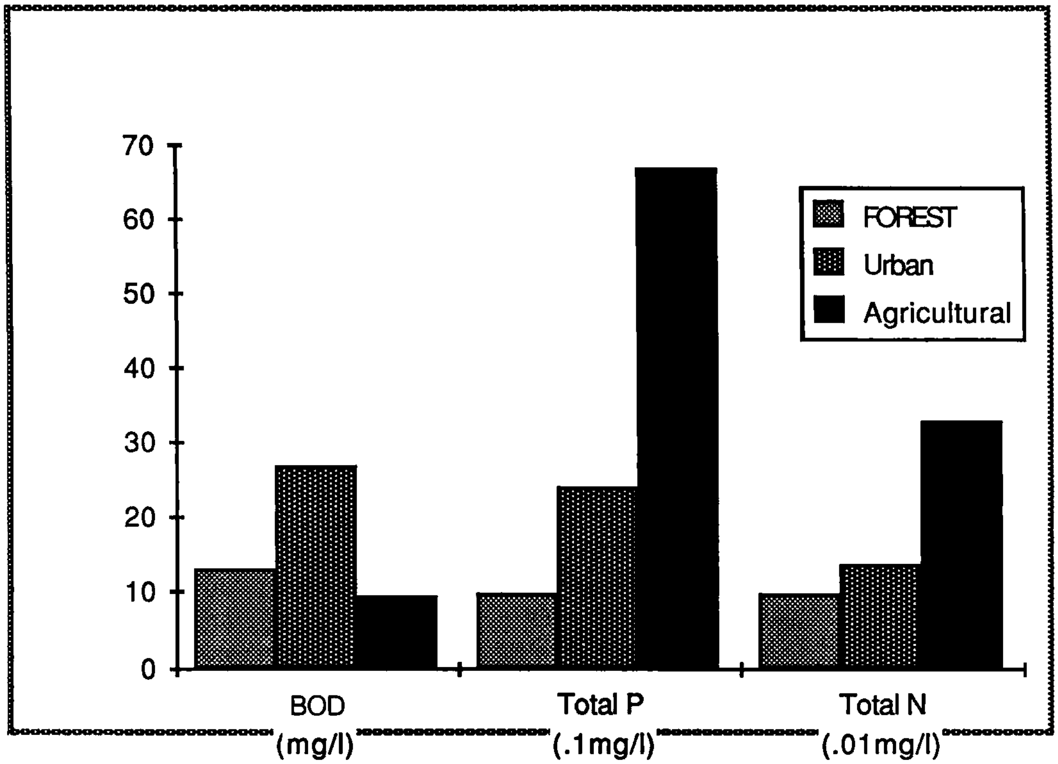
PERCENTAGE OF LAND USE TYPE FOR THE 9 CONSOLIDATED PLANNING BASINS OF THE PUGET SOUND WATER QUALITY PLANNING AREA



PUGET SOUND WATER QUALITY AUTHORITY

Figure 45

NONPOINT SOURCE CASE
STUDY WATERSHEDS



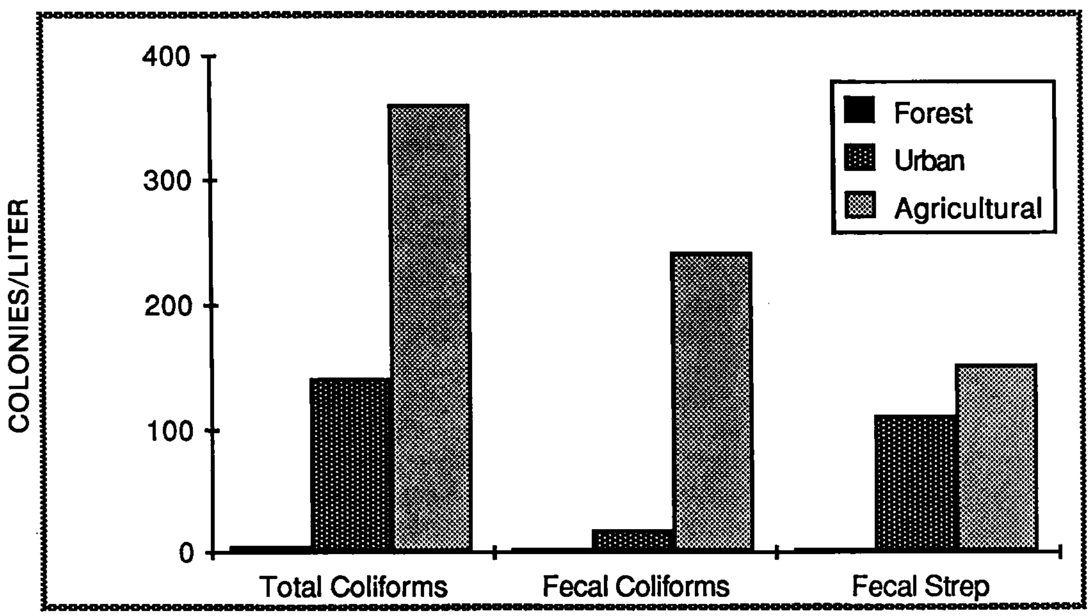


Figure 46

AVERAGE STORM RUNOFF CONTAMINANT CONCENTRATIONS BY LAND USE TYPE FOR THE NEWAUKUM CREEK WATERSHED

over a one-year period from each type of land. Concentrations of nutrients (phosphorus and nitrogen), bacteria, and BOD were highest in stormwater runoff from the agricultural land, which accounted for 79 to 92 percent of contaminant loading (Figure 47) in this watershed.

Forested Land Use

Forested land comprises from 63 to 92 percent of nine Puget Sound watersheds (Figure 44) and 82 percent overall. Typical forest practices that have been linked to nonpoint contamination and water quality problems include: logging road construction, maintenance, and abandonment; clearcut and partial cut practices; salvage logging; site preparation; herbicide and pesticide spraying; and management of logging slash and debris.

Some data on contaminant loadings are available for the predominantly forested Big Beef Creek watershed in Kitsap County (Figure 45). The creek drains about 38 square kilometers (15 square miles), and the watershed consists of about 85 percent forested land. The principal activities in the watershed since 1850 have been logging and some cattle grazing. Most virgin timber was harvested by 1930, and logging of second-growth timber was initiated in the mid-1950s. The deforested fraction of the watershed was three percent in 1942 and 12 percent in 1965. Currently, it is approaching 20 percent.

The amount of sediment entering Big Beef Creek is influenced by natural processes (e.g., creep and mass movement of soil) and by human actions such as logging, road construction, and land clearing. Estimates (Figure 48) have been made of the annual sediment loading to the creek comparing undisturbed watershed conditions and disturbed conditions. It is obvious in this example that human influence on a watershed's land use can have significant effects on water quality. Figure 49 provides an estimate of the contribution of sediment to Big Beef Creek from human influence and from natural erosion processes. Over 50 percent of the sediment loading is estimated to come from erosion of unpaved road surfaces.

Over 80 percent of the Puget Sound basin is forested. Agricultural and urbanized lands each cover about eight percent of the basin (about two percent is open fresh water). However, because rainfall is heavier in the forested foothills and mountains than in the more developed lowlands, it is estimated that 92 percent of the water entering Puget Sound fell as rain or snow on forested land, about five percent on agricultural land, and three percent on urban areas. Each year about 50,000 acres of timber are harvested in the Puget Sound basin. Although the area harvested each year is less than the acreage in urban land use, it is greater than the amount of land converted to urban uses each year. Thus, forest practices have the potential to significantly influence water quality.

Urban/Suburban Land Use

Urban and suburban areas cover from one to 24 percent of the nine Puget Sound watersheds (Figure 44). Land development dramatically changes the way water interacts with the land. Normally absorbent soil is covered with roads, rooftops, parking lots, and other impervious surfaces. This increases the flow of surface water, and contaminants such as oil, fertilizer, household products, and sediment degrade the quality of stormwater runoff.

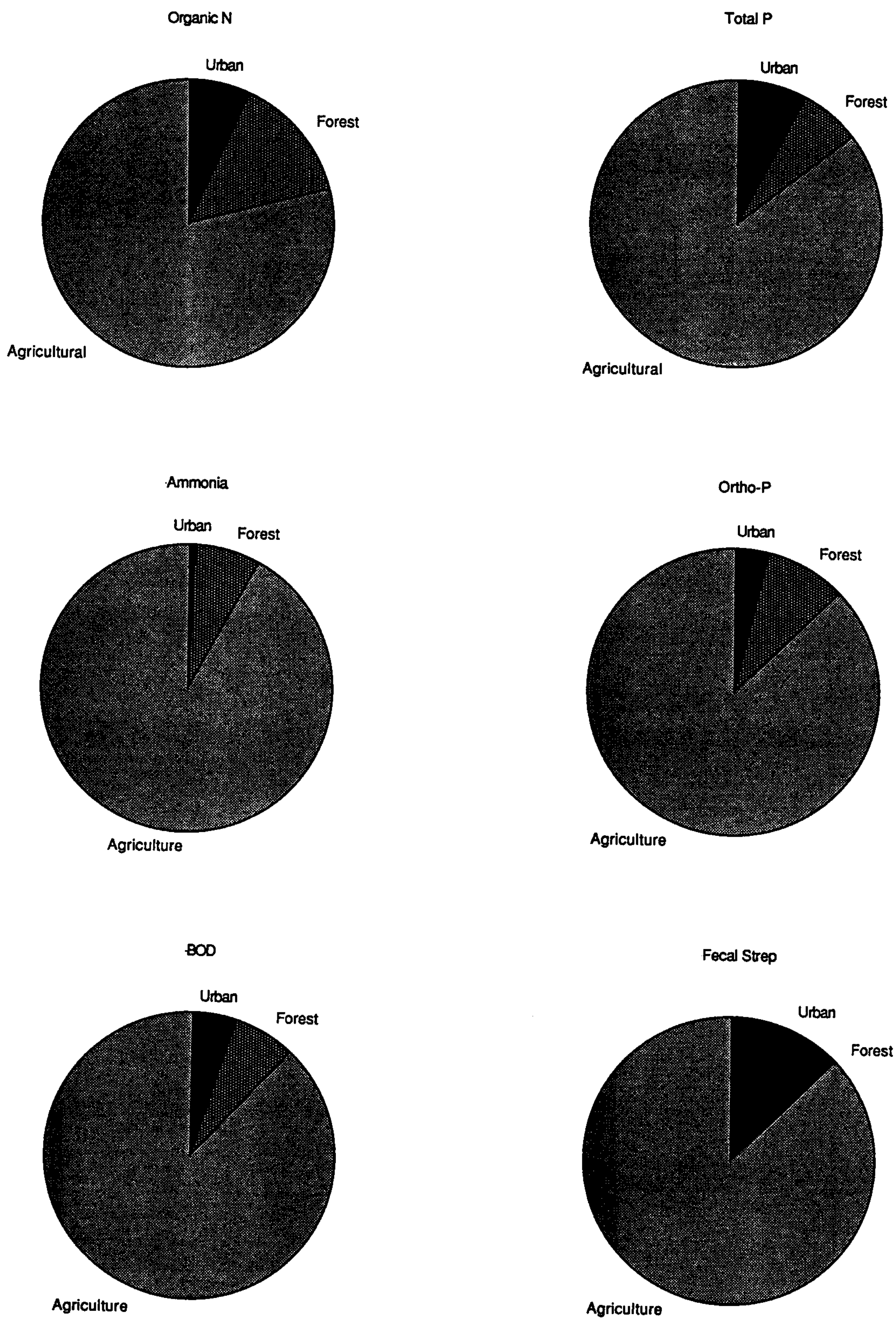


Figure 47

NONPOINT SOURCE LOADING TO NEWAUKUM CREEK FROM VARIOUS LAND USE TYPES

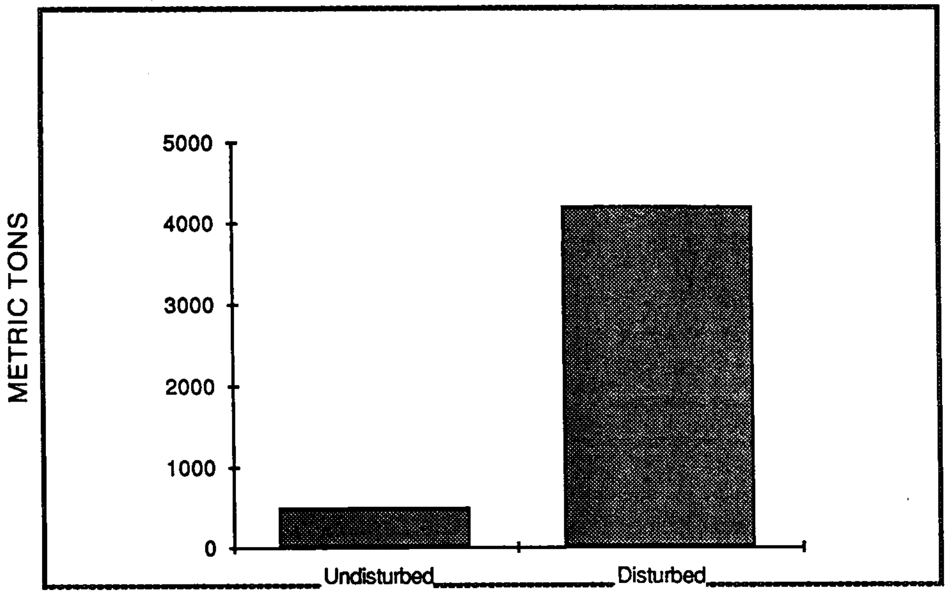


Figure 48

ANNUAL STREAM SEDIMENT LOADING ESTIMATES FOR DISTURBED AND UNDISTURBED AREAS OF BIG BEEF CREEK WATERSHED

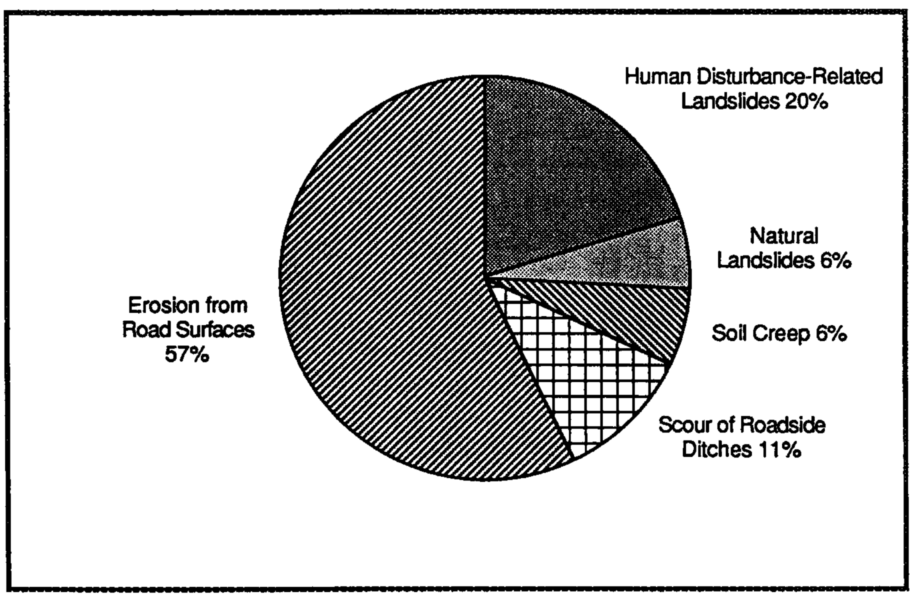


Figure 49

PERCENT OF SEDIMENT LOADING TO BIG BEEF CREEK FROM VARIOUS EROSIONAL SOURCES

The Bear-Evans Creek watershed in northeastern King County (Figure 45) illustrates the potential effects of urbanization on water quality. The creek system drains 128 square kilometers (50 square miles), and the watershed currently consists of five percent agricultural land, 71 percent forested land, and 24 percent urban/suburban land.

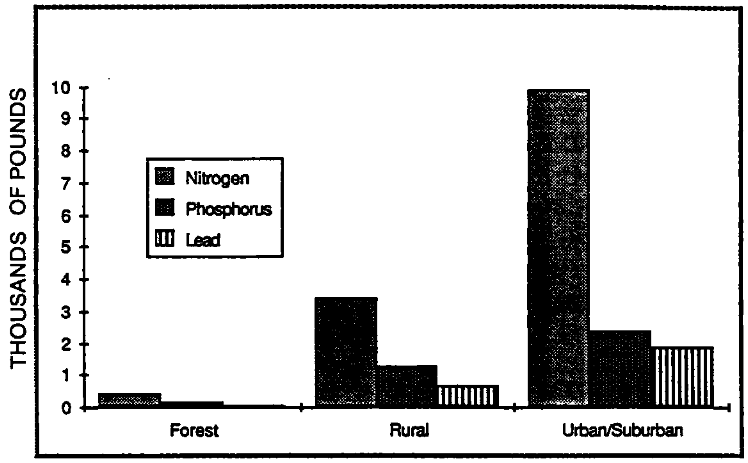
Contaminant loads have been forecast for different future patterns of development in the watershed using a water quality prediction model developed by the Municipality of Metropolitan Seattle (Metro). For this example, two land use alternatives were used based on planning done by King County (Table 14). The first assumes the watershed will remain relatively rural in nature, and the second assumes predominantly urban land use. A third alternate in which unharvested forest would cover the entire watershed is included for comparison.

TABLE 14: BEAR-EVANS CREEK WATERSHED--ASSUMED ACREAGES OF PARTICULAR LAND USES

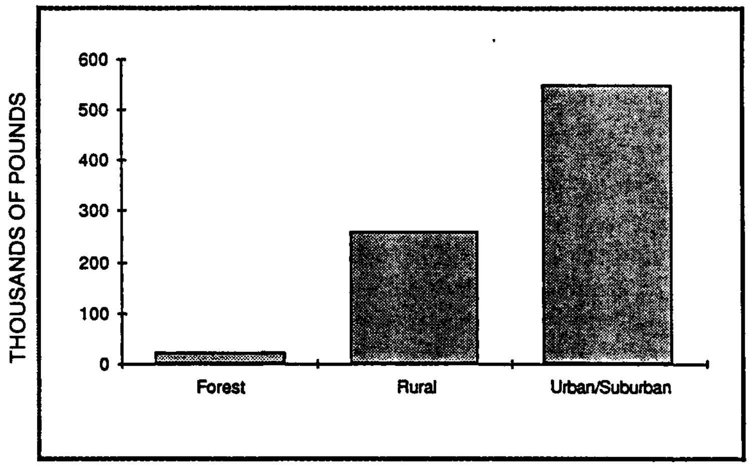
Land Use	Forested	Rural	Urban/Suburban
Rural	0	11,655	5,110
Low Density	0	4,301	3,960
Medium Density	0	223	7,570
Multiple Family	0	0	275
Commercial	0	37	116
Industrial	0	516	719
Forested	17,732	0	0
TOTAL	17,732	16,732	17,750

Results of the study (Figure 50) predict that runoff from urban/suburban land use is far more contaminated than that from rural land use. Both of these alternatives produce greater loadings than that featuring the unharvested forest (which approximates conditions throughout the basin 200 years ago.)

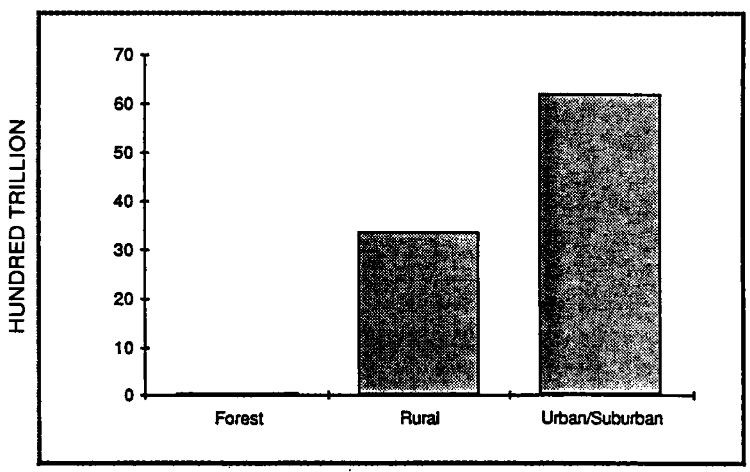
Bear Creek is located well upstream of Puget Sound. Other studies have considered low-density residential development along the Sound's shore. In 1983 the Washington State Department of Ecology assessed Burley Lagoon and Minter Bay and their respective watersheds in Kitsap and Pierce Counties to determine local factors affecting shellfish contamination. The watersheds draining into Burley Lagoon and Minter Bay each cover approximately 40 square kilometers (10,000 acres). Both are rural areas located within commuting distance of rapidly expanding urban communities. Recent development has been rapid, and the population in each watershed nearly tripled between 1970 and 1980. At present, approximately 27 percent of the land in the Burley watershed and 35 percent in the Minter watershed is developed; the balance is largely forest land. Most development consists of small farms and residential



NITROGEN. PHOSPHORUS AND LEAD



SUSPENDED SOLIDS



FECAL COLIFORM BACTERIA

Figure 50

LOADING OF CONTAMINANTS TO BEAR CREEK FROM DIFFERENT LAND USE TYPES

tracts which began along roads and streams in the lowland areas and are now advancing toward the upland forested areas.

The soils in the Burley and Minter watersheds, like those in much of western Washington, do not drain well. Approximately three-quarters of the area in the Burley watershed and half of that in the Minter watershed are mapped as restricted for on-site disposal of sewage (i.e., septic tanks). Yet, the area is not sewered and relies on septic systems. High levels of fecal coliform bacteria, often violating state water quality standards, were found in streams and ponds in the developed areas of both watersheds, while waters in the undeveloped areas were not contaminated. About three-quarters of the stream areas examined in the Burley watershed and half of those in the Minter watershed contained unacceptable levels of bacteria. Streams that flowed from developed areas to undeveloped areas showed higher levels of bacteria in the developed areas than in the natural areas.

Failing septic tanks from shoreline homes did not generally contribute to the problem in Minter Bay; however, they were identified as a source in Burley Lagoon. Water entering Minter Bay from Puget Sound was found to be low in fecal bacteria. Sea birds were also found to contribute little contamination.

Eld and Henderson Inlets are narrow bays in southern Puget Sound that support a rich commercial shellfish industry. In recent years there have been closures of commercial shellfish beds in these areas due to contamination by fecal coliform bacteria. In 1984 the Thurston County Health Department undertook a year-long study of bacterial contamination threatening the shellfish resource. The study examined marine waters in the inlets, along shorelines, and in streams in the respective watersheds.

The lands surrounding Eld and Henderson Inlets are relatively undeveloped and contain few major urban or industrial land uses. The watershed surrounding Eld Inlet is almost completely rural in nature, while the Henderson watershed has more residential, commercial, and small farm development.

Fecal coliform concentrations in seawater samples from Henderson Inlet violated state water quality standards part of the time, while samples from Eld Inlet were somewhat cleaner. Stream waters in the Henderson watershed violated bacterial contamination standards 61 to 92 percent of the time, compared to a violation rate of 0 to 25 percent in Eld streams. It was also found that wet weather tended to increase the level of fecal coliform bacteria in the marine waters due to increased runoff.

Water quality violations in Henderson Inlet were attributed to surface stormwater runoff, poor management practices for farm animals and pastureland, and failing on-site septic systems. Twelve failing septic systems were found in the Henderson watershed, which contributed approximately 14 percent of the total bacterial contamination found in the inlet under worst case conditions. A single municipal stormwater drain accounted for 18 percent of the total bacterial contamination.

Stormwater samples from Eld Inlet showed levels of fecal contamination throughout most of the year. Fecal contamination is a major threat to the

waters and shellfish of Eld Inlet, but the incidence of water quality violations is much lower and the sources are less apparent than those of Henderson Inlet. Unfortunately, these studies did not investigate loadings of toxic organics from septic systems or rural runoff.

The implications of rural shoreline development are especially important because such areas are growing rapidly throughout the Sound. Between 1970 and 1980, the fastest growing counties were the more rural ones--San Juan, Island, Thurston, Jefferson, Mason, and Clallam. Especially on San Juan, Whidbey, and Camano Islands, this growth represents an increasing trend toward recreational subdivisions, second homes, and retirement communities, many of which are on or near the water. Most of the new subdivisions in these areas are using on-site septic systems. Table 15 shows the current number of on-site systems by county.

TABLE 15: ON-SITE SEWAGE SYSTEMS IN 1985 BY COUNTY

County	Number of Systems	Permanent Households	Percent of All Households
Clallam	13,034	23,562	55%
Island	41,856	23,826	*
Jefferson	8,379	9,998	84%
King	61,500	478,906	11%
Kitsap	34,166	65,979	52%
Mason	15,326	20,238	76%
Pierce	88,000	201,478	44%
San Juan	8,107	6,128	*
Skagit	13,931	30,188	46%
Snohomish	58,000	150,968	38%
Thurston	20,000	58,078	34%
Whatcom	20,835	50,869	41%
TOTAL	383,134	1,220,218	

(Source: Washington Department of Social and Health Services, Washington Office of Financial Management.)

Notes: DSHS data are based on 1975 survey and 1980 U.S. Census data projected to 1985. The number of on-site systems in Pierce County will be reduced soon due to the formation of the Lakewood Sewer District.

* The number of on-site systems in San Juan and Island Counties exceeds the number of households, probably due to the number of vacation homes in these areas. There are several municipal sewage systems in these counties.

According to the Washington State Department of Social and Health Services, there are approximately 383,000 on-site systems in the 12-county Puget Sound region. Every year, there are about 10,000 new systems added, or about

one-third of the new housing units in the region. At any one time, there is an estimated failure rate of 3.5 to five percent; this estimate is based on observation, fecal coliform counts, and county health department data. Thus the potential growth of this source of contamination must be considered seriously in land use and water quality planning. Most failures occur in older systems, many of which do not meet modern standards. But new systems will also age and must be properly sited and maintained.

Wastewater Streams

Point and nonpoint wastewater streams can be analyzed and identified by the classes of contaminants that are expected to occur in each. Industrial and commercial wastewaters contain pathogens, toxic metals, toxic organic chemicals, BOD, nutrients, and sediment. Residential wastewater (domestic sewage) contains pathogens, toxic organic chemicals, BOD, nutrients, sediment, and some toxic metals. Urban stormwater contains pathogens, toxic metals, toxic organic chemicals, BOD, nutrients, and sediment. Rural stormwater contains pathogens, BOD, nutrients, and sediment. Agricultural runoff contains pathogens, BOD, nutrients, sediment, and occasionally toxic chemicals. Finally, runoff caused by forest practices contains sediment and occasionally toxic chemicals.

DISTRIBUTIONS AND TRENDS OF CONTAMINATION

Much of the current concern about contamination of the Puget Sound basin is focused on toxic chemical contamination and pathogens which pose a risk to human health. However, Puget Sound has suffered serious damage in the past from discharges of conventional contaminants (especially BOD, pathogens, and nutrients) that are today generally controlled, at least from point sources.

HISTORIC CONTAMINATION IN THE PUGET SOUND BASIN

The environmental effects of the discharge of pulp wastes into Puget Sound do not stand out in the historical records before the 1920s. Shortly after the introduction of the pulp mills, oysters and other shellfish began to disappear from the bays near Shelton, Anacortes, Everett, Port Angeles, and Bellingham, in areas adjacent to the mills. In 1926 it was reported to a Washington Department of Health official that ship worms had been killed on a wharf adjoining a pulp mill and that crabs were no longer found near the site. For a period of 10 to 15 years, fishermen mooring in Everett Harbor had no need to paint their boats with anti-fouling paint because fouling organisms could not survive in the contaminated water. Timber pilings in Elliott bay were also largely protected from marine boring organisms by the levels of pollution. Oyster growers in the 1920s and 1930s blamed the pulp mills of southern Puget Sound for the decline of the Olympia oyster industry. It was also commonly believed that, prior to installation of contamination controls, pulp mill discharges damaged the salmon runs from the Stillaguamish and Snohomish Rivers. The contribution of overharvesting--another important factor--is unknown for these situations.

The conflict between the oyster growers and the pulp mills was the first real water quality issue in Puget Sound. In 1945, the state legislature passed a bill

TABLE 16: SELECTED TOXIC CONTAMINANT DISTRIBUTIONS IN THE PUGET SOUND BASIN[1]

	Water[2]	Sediment	Tissue
PAH	Detected at very low concentrations (.01 ppb) in waters of Puget Sound Central Basin. Mostly associated with particulates suspended in water.	Elevated concentrations (from 10x to 420x reference) in industrialized urban areas. Eagle Harbor has highest elevation measured.	Mainly in invertebrates; some in fish livers; rarely in fish muscle tissue. Elevated levels in invertebrates from Eagle Harbor, Mulkiteo ferry dock area.
PCBs	Detected at very low concentrations (.001 to .01 ppb) in waters of Puget Sound Central Basin. Mostly associated with particulates suspended in water.	Elevated concentrations (from 20x to 130x reference) in industrialized urban areas with exception of Bellingham Bay.	Found in nearly all organisms from nearly all areas; highest levels in fatty tissues of marine mammals with long lifespans (e.g., harbor seals from southern Puget Sound).
Copper	Detected at very low concentrations (.1 to 1 ppb) in waters of Puget Sound Central Basin.	Elevated concentrations (from 10x to 370x reference) in Elliott Bay, Hylebos Waterway, Everett Harbor, Bellingham Bay, Eagle Harbor and Sinclair Inlet. Highest elevation along Ruston-Point Defiance shoreline, Commencement Bay.	Copper can accumulate in tissues of bivalve mollusks, crustacea, fish livers, and birds in industrialized urban areas. Copper is a natural component of the blood of crabs, snails and some other invertebrates. Significant accumulation of copper in fish muscle tissue from several areas of Commencement Bay.
Lead	Detected at very low concentrations (1 to 10 ppb) in waters of Puget Sound Central Basin.	Elevated concentrations (from 10x to 110x reference) in Elliott Bay and Sinclair Inlet. Highest elevation along Ruston-Point Defiance shoreline.	Lead can accumulate in tissues of bivalve mollusks, crustacea, fish livers, and birds in industrialized urban areas. Lead does not generally accumulate at high levels in fish muscle tissue.
Zinc	Detected at very low concentrations (1 to 10 ppb) in waters of Puget Sound Central Basin.	Elevated concentrations (from 10x to 43x reference) in Elliott Bay, Duwamish River, Ruston-Point Defiance (43x reference), Everett Harbor, Sinclair Inlet.	Zinc can accumulate in tissues of bivalve mollusks, crustacea, fish livers, and birds in industrialized urban areas. Zinc does not generally accumulate at high levels in fish muscle tissue.
Mercury	Detected at very low concentrations (<.001 ppb) in waters of Puget Sound Central Basin.	Elevated concentrations (from 10x to 170x reference) in Elliott Bay, Ruston-Point Defiance (170x reference), Bellingham Bay, and Sinclair Inlet.	Historically high concentrations in mussels from Bellingham Bay. Mercury can accumulate in tissues of bivalve mollusks, crustacea, fish livers, and birds in industrialized urban areas. Mercury has not been found to accumulate at high levels in fish muscle tissue from Puget Sound, but does in fatty tissues of long-lived marine mammals (probably as methyl mercury).
Arsenic	Detected at very low concentrations (1 to 10 ppb) in waters of Puget Sound Central Basin.	Elevated concentrations (from 10x to 620x reference) in Hylebos Waterway and Ruston-Point Defiance (620x reference) shoreline.	Arsenic levels in invertebrates, fish, and birds from areas containing contaminated sediments are similar to those in reference areas. A naturally high level of arsenic in seawater in the Northeast Pacific and Puget Sound is a major source of arsenic in organisms.

[1]These toxic contaminants are selected because they have been the most studied. Many other toxic compounds are known to be present in harmful amounts.

[2]From Romberg et al., 1984.

establishing an independent pollution control board. Coincidentally, at about the same time, the Shelton mill that had damaged the commercial oyster industry in the 1920s instituted a new treatment process.

Mercury contamination was observed in Bellingham Bay during the late 1960s.

Industries were not the only polluters of the past--sewage was discharged without treatment. The many coastal towns at first discharged raw sewage directly to saltwater. For example, by the turn of the century beaches on Elliott Bay were too contaminated for swimming. The first major sewage systems were developed in cities during the first decades of the twentieth century. In Seattle the earliest system was built between about 1910 and 1925. It discharged into Puget Sound. However, settlement began to occur near Lake Washington. By 1922, 30 raw sewage outfalls ran into Lake Washington, serving a population of about 50,000.

The first Federal Water Pollution Control Act was enacted in 1948. In 1951 the federal government reported that Puget Sound was the sixth most polluted area in the country based on severity of oxygen depletion. In Everett Harbor, fish kills ranging from one or two individuals to "barrels full" were reported nearly daily. A large portion of the bottom of Port Gardner, covered by a deposit of rotting organic matter consisting of sewage, fish cannery waste, and pulp mill waste, was unable to support species like flounder, sole, and shrimp, and was nearly devoid of any animal life. Other waterways were similarly damaged. In 1955, the state passed legislation requiring dischargers to have permits to dump wastes into the public waters.

At about this time the pollution of Lake Washington became an issue of local concern. The combination of partly treated sewage and failing septic systems had made the water unfit for swimming. Excess nutrients had stimulated plant growth, clouding the waters. Puget Sound beaches were also closed because raw sewage was dumped into Salmon Bay and Elliott Bay. A proposal creating the Municipality of Metropolitan Seattle (Metro) was passed in September of 1958. The special district constructed a sewer line around Lake Washington and ran sewage to a treatment plant and then into Puget Sound. The Metro sewer project was one of the nation's first major commitments to fighting water pollution, and by 1970 nutrient problems in Lake Washington had largely been solved.

Substantial control of contaminant discharges has been achieved by industry and municipal treatment plants. Pulp mills have reduced BOD discharges from 2,000,000 pounds per day in 1969 to less than 30,000 pounds per day in 1983.

PRESENT LEVELS OF CONTAMINATION

Nutrients and BOD

Although the huge discharges of oxygen-demanding wastes from mills and untreated sewage have been largely controlled, fish kills do occur in localized areas of southern Sound bays when organic matter (BOD) decomposes and uses up all the oxygen. In some parts of the Sound such anoxic events occur naturally following annual population explosions (and subsequent die-offs) of algae.

Nutrients are not generally a problem in the marine waters of the Puget Sound basin except in specific locations with special water column characteristics. This is because, in most of the marine waters of the basin, the growth of phytoplankton is controlled by light and the stability of the water column rather than by nutrient levels. But in Budd Inlet natural stability in the water column allows periodic blooms which result in low oxygen conditions.

Groundwater Contamination

Some groundwater aquifers in the Puget Sound basin are experiencing water quality problems in localized areas. Examples include the intrusion of salt-water into aquifers in the San Juan Islands and Whidbey Island and along stretches of shoreline elsewhere in the Sound. Hazardous waste is known to have contaminated some aquifers in the Kent and Tacoma areas, and chemicals have leached from landfills in both King and Pierce Counties to contaminate groundwater. In addition, iron contamination of domestic water wells is not uncommon. Farm chemicals including fertilizers and pesticides have been discovered in some wells in the region, although these problems tend to be very localized. Contamination of groundwater can be an early warning that contaminants are being released into the larger environment. Not only does the groundwater become unusable, the groundwater eventually reaches the Sound with its load of contaminants.

Toxic Chemical Contamination

The data below highlight the areas in the Puget Sound basin where certain toxic chemical contaminants have been reported, and indicate the approximate concentrations found. Because chemicals of concern are found in higher concentrations in the sediment and tissues than in the water, most samples focus on sediment or plant and animal tissues. Available studies have concentrated on locations near urban areas where most chemical contamination is expected to occur. The data tend to under-represent large areas of the Sound in which no studies have been conducted. Measurements of those areas are needed to confirm any overall picture of contamination in the Sound.

Severe chemical contamination of Puget Sound (as measured in sediments and animal tissues) appears as a patchy distribution, generally confined close to sources. Consequently, studies have focused on small areas with the worst problems. However, of the thousands of chemicals known or suspected to exist in the environment, only a small number can be measured routinely in detailed environmental studies. The chemicals chosen for study are often dictated by our ability to detect them. They typically have: a demonstrated or suspected effect on human health or marine life; one or more present or past sources (to the Sound) that are large enough to be of concern; a potential for persisting in a toxic form for a long time in the environment; and a potential for entering the food web.

Reliable surveys have been conducted for up to 150 toxic chemicals near urban areas of Puget Sound. Several hundred other synthetic organic chemicals have been tentatively identified in Puget Sound sediments. Chemicals that have been frequently detected and reported are polychlorinated biphenyls (PCBs), pesticides such as DDT, heavy metals, and two classes of organic chemicals called phenols and polynuclear aromatic hydrocarbons (PAHs). PAHs originate mostly from burning of natural organic compounds such as wood, coal and oil;

some of this burning has always occurred (forest fires), but it has been greatly accelerated in modern society. PAHs also are found in unburned oil products.

An overview of our current understanding of the distribution of PAHs, PCBs, copper, lead, zinc, mercury, and arsenic in Puget Sound is presented in Figures 51, 52, and 53 and Tables 16 and 17. These contaminants were selected because they are those most studied. Bars shown in the figures represent the average concentrations of contaminants in surface sediments in different areas of the Sound. The lines extending above the bars show the maximum level reported.

The heavily industrialized areas of Seattle (e.g., the West Waterway of the Duwamish River) and Tacoma (e.g., Hylebos Waterway) are among the most contaminated and contain a complex mixture of toxic substances. Eagle Harbor, west of Seattle at Winslow, is highly contaminated in small areas with hydrocarbons likely derived from creosote which was used to treat wood at a nearby factory. Some areas that were of concern in the past are now less contaminated. For example, mercury contamination observed in Bellingham Bay during the late 1960s has lessened since its source has been controlled. The harbors of Everett and Bremerton (Sinclair Inlet) have received sufficient study to identify them as areas of high contamination, but not enough to define clearly all of the major chemicals present or their distributions.

Areas that have intermediate levels of contamination (e.g., central Puget Sound between Seattle and Tacoma) are predominantly affected by the transport of contaminants by water currents from areas with major sources. Areas with low contaminant levels are generally far from major development. Even in these areas, natural transport by air and water has introduced some contaminants. It is likely that no area of the Sound is completely free from some contamination by toxic chemicals.

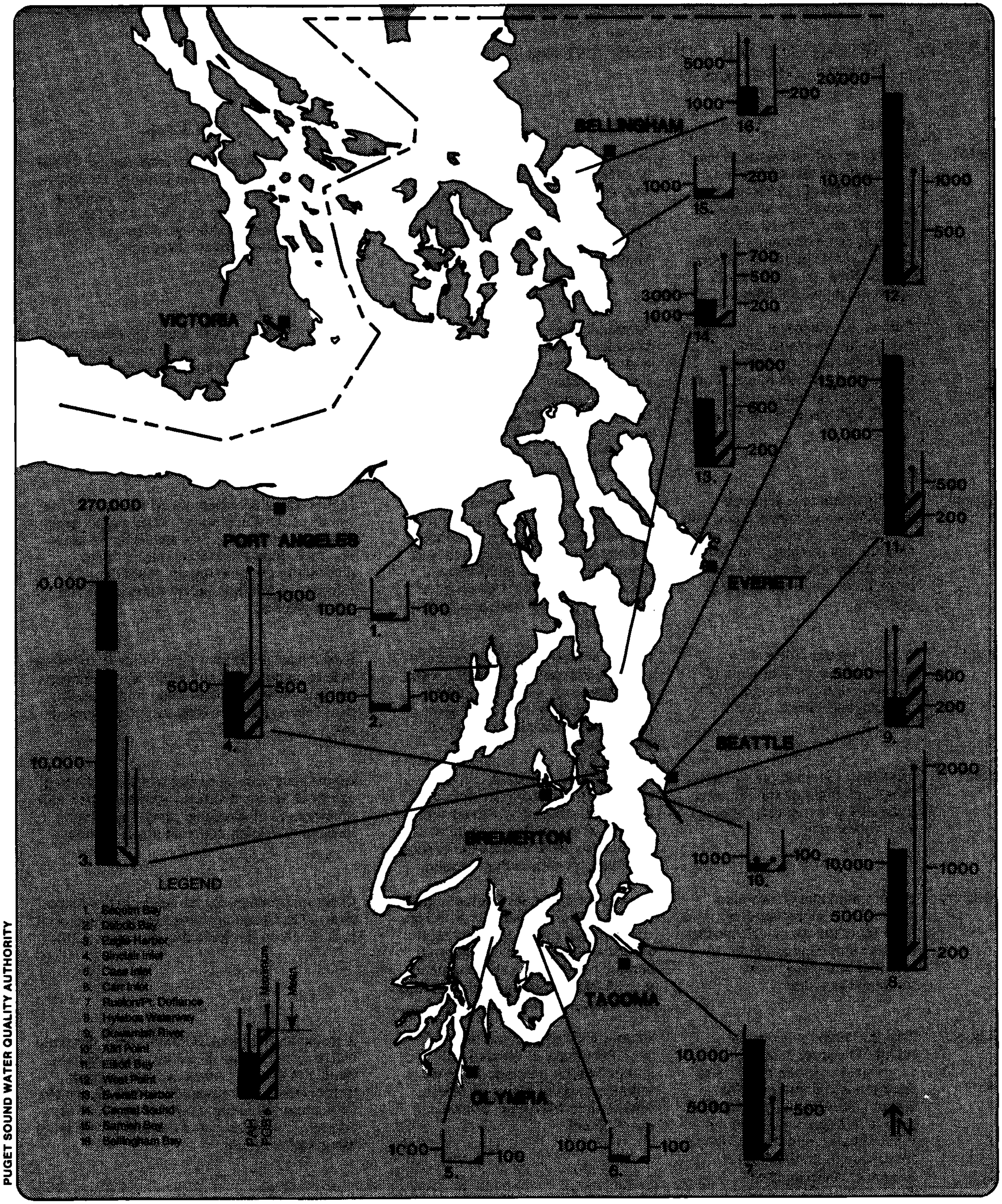
One way to judge the severity of contamination at a given location is to calculate an enrichment factor that compares contaminant levels in an affected area to those from a site with the lowest measured levels. This enrichment factor is the ratio of the contaminant concentration in contaminated sediments to the average concentration in sediments from a non-urban, relatively uncontaminated reference area. A summary of these values for different contaminants and areas (Figure 54) indicates that enrichment factors for metals are less than 100 everywhere except off of the Ruston/Point Defiance shoreline near the main outfalls of the now closed ASARCO copper smelter. Enrichment factors of several organic compounds at the ASARCO site often exceed 100 and occasionally even exceed 1,000.

Sediments continually accumulate on the bottom of Puget Sound; newer deposits bury older sediments. The approximate date that sediments were deposited can often be estimated using radiocarbon dating methods. By measuring the contaminant concentrations in different sediment layers, the history of contamination can be evaluated. Detailed historical sediment data exist only for some contaminants in Puget Sound. Historical trends in contamination of central Puget Sound sediments by PCBs, PAHs, and lead are shown in Figure 55 and Table 17. Concentrations of contaminants are low in

TABLE 17: SELECTED TOXIC CONTAMINANT SOURCES, EFFECTS AND TRENDS IN THE PUGET SOUND BASIN[3]

	Sources	Effects	Trends
PAH	Variety of natural and anthropogenic sources including local fragment runoff from forest fire areas, automobile crankcase oil, crude oil and oil by-products (such as creosote), and combustion of organic material. Present in municipal effluents, runoff, and some industrial effluents.	Potentially associated with altered benthic communities, sediment toxicity, and histopathological conditions in fin fish--no cause/effect relationships have been proven. Some PAH metabolites are carcinogenic and have been found in fish livers and bile.	In general, concentrations have declined since the 1950s, but distribution is highly dependent on proximity to source. Inputs will probably not vary considerably in near future due to variety of sources, although effects of population increase may cause increases.
PCBs	Coolant for electrical components such as transformers and capacitors now banned from production, but still in use. Can enter Puget Sound through runoff, spills, and illegal dumping.	Potentially associated with altered benthic communities, sediment toxicity, and reproductive failure in some marine mammals and birds--no cause/-effect relationships have been proven. In California, PCB metabolites have been found in mussels, shrimp, and some fish livers. These metabolites have not been studied in Puget Sound.	Concentrations in most areas have decreased over time probably due to ban on manufacture. Barring wide-spread spills, dumping, or release from landfills, decrease should continue.
Copper	Principal source is probably municipal water supply pipes, also present in some industrial effluent, smelter slag, and as a component of some wood treatment, paint, and sand-blasting products.	Essential nutrient (especially for crustaceans) at low concentrations, can be acutely toxic at high concentrations. Potentially associated with altered benthic communities and sediment toxicity. No cause/effect relationships have been proven in Puget Sound.	Inputs have decreased due to water softening by city of Seattle, however, more copper pipe is coming into use as sold steel/zinc pipes are replaced. Inputs will likely remain fairly constant in the near future, dependent on effect of population increase and industrial developments.
Lead	A major source is lead in gasoline. Present in urban and highway runoff, some industrial effluent, and smelter slag.	Can be acutely toxic at high concentrations. Potentially associated with altered benthic communities and sediment toxicity. No cause/effect relationships have been proven in Puget Sound.	Inputs have decreased due to drastic reduction in lead content of gasoline. Observed concentrations will likely follow same trend through near future, but then follow trend in gasoline use.
Zinc	Municipal water supply pipes, urban and highway runoff, some industrial activities (e.g., plating), and smelter slag.	Essential trace nutrient, can be acutely toxic at high concentrations. Potentially associated with altered benthic communities and sediment toxicity. No cause/effect relationships have been proven in Puget Sound.	Inputs have decreased due to water softening by city of Seattle and other municipalities, and replacement of steel/zinc pipes. Inputs will likely remain fairly constant in near future.
Mercury	Historically from chloro-alkal plants (e.g., Bellingham Bay). Also from other industrial/commercial services including smelter activities and some wood treatment products.	Acutely toxic to many marine organisms, in organo-metallic form, at high concentrations. Can bioconcentrate. Potentially associated with altered benthic communities and sediment toxicity. No cause/effect relationships have been proven in Puget Sound.	Concentrations in dogfish have declined since mid-1970s. Concentrations in surface sediment in Bellingham Bay have declined since 1970s.
Arsenic	Principal single source was ASARCO copper smelter. Also component in urban runoff, and some industrial effluent. The largest (mass-loading) sources of arsenic to Puget Sound are the Pacific Ocean, and Puget Sound area rivers, from the natural erosion of rocks and soils.	Acutely toxic to most marine organisms. Potentially associated with altered benthic communities and sediment toxicity. No cause/effect relationships have been proven in Puget Sound.	A major source (ASARCO) has been discontinued, concentrations in sediment and biota in vicinity of smelter should decrease in near future. Other concentrations will likely remain fairly constant, except may also decrease as controls are implemented on runoff from areas using slag or ballast.

[3] These toxic contaminants are selected because they have been the most studied. Many other toxic compounds are known to be present in harmful amounts.



PUGET SOUND WATER QUALITY AUTHORITY

Figure 51

DISTRIBUTION OF PAHs AND PCBs IN PUGET SOUND SEDIMENTS

(CONCENTRATION IN PPB DRY WEIGHT)

PUGET SOUND WATER QUALITY AUTHORITY

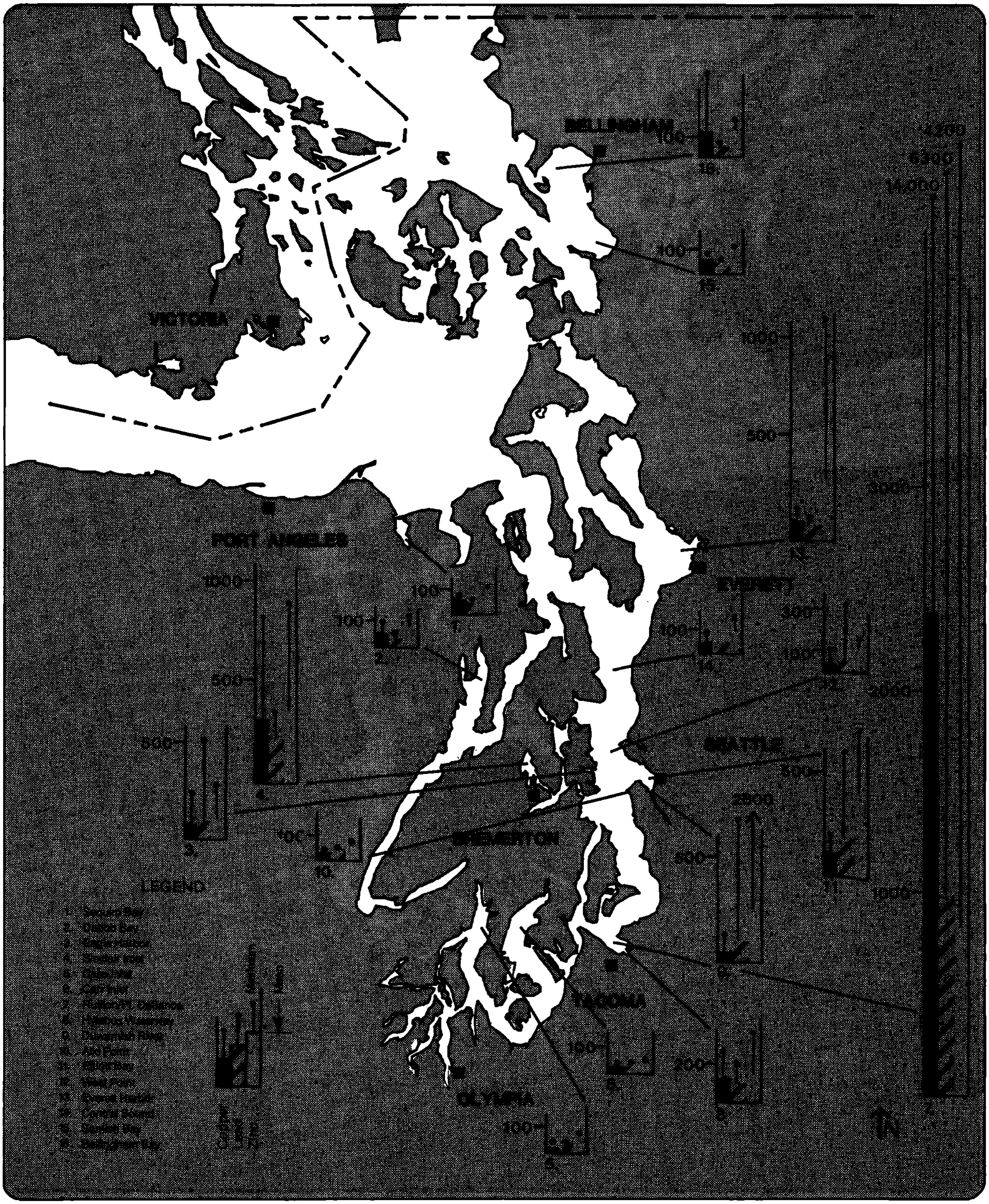
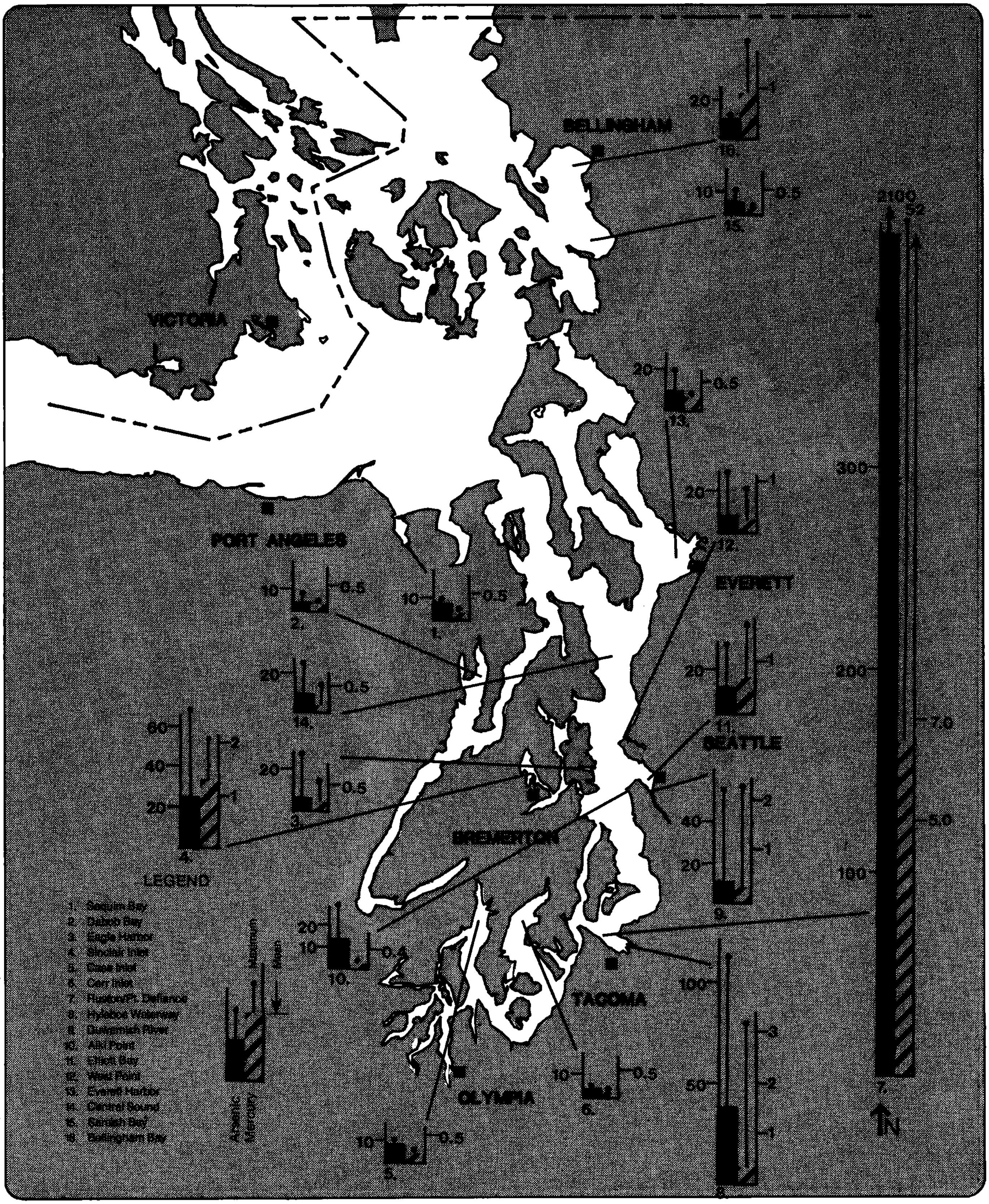


Figure 52

DISTRIBUTION OF COPPER, LEAD, AND ZINC IN PUGET SOUND SEDIMENTS

(CONCENTRATION IN PPM DRY WEIGHT)



PUGET SOUND WATER QUALITY AUTHORITY

Figure 53

DISTRIBUTION OF ARSENIC AND MERCURY IN PUGET SOUND SEDIMENT

(CONCENTRATION IN PPM DRY WEIGHT)

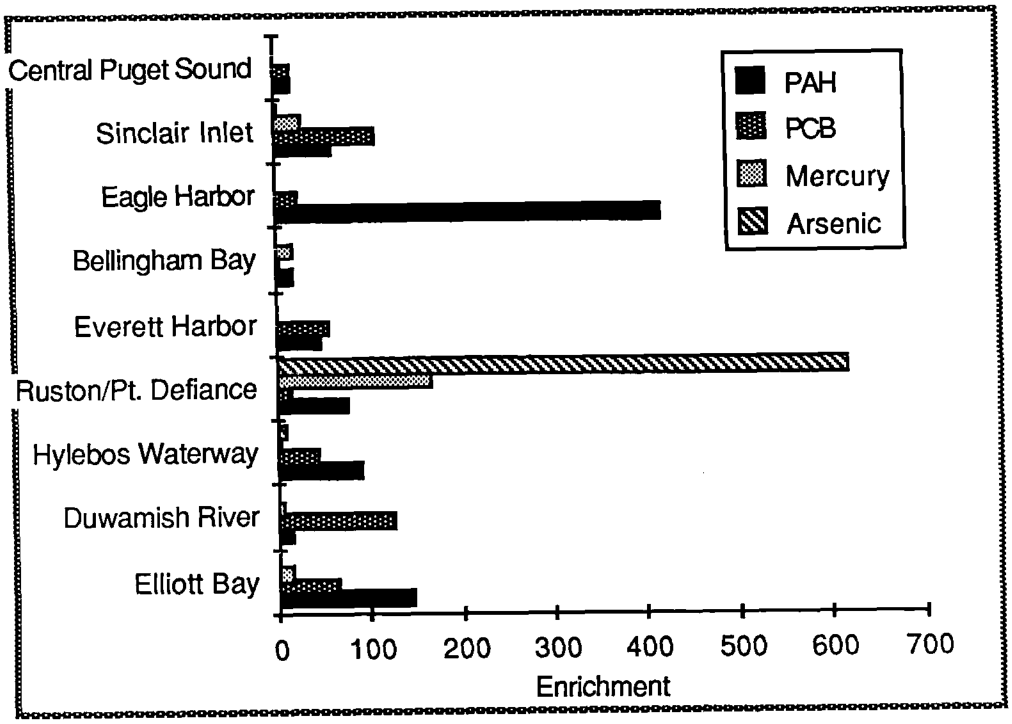


Figure 54

ENRICHMENT FACTORS FOR CONTAMINANTS IN PUGET SOUND

sediments that were deposited in Puget Sound before about 1880. The late 1800s correspond to the beginning of major urban development of the region.

PCBs have been manufactured only since the 1930s. Concentrations of PCBs in sediments show a corresponding increase at that time followed by a decrease since their manufacture was banned in the early 1970s.

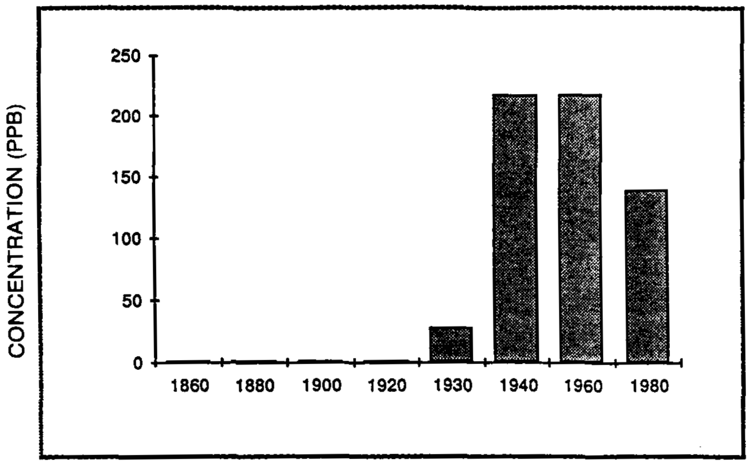
PAHs have natural sources (e.g., forest fires), but a significant increase in their concentration is observed in sediments in central Puget Sound dating from the turn of the century up until the 1950s, corresponding to the period of rapid growth in the use of motor oil and fossil fuels. The 1950s PAH concentrations are approximately two to three times present-day concentrations and over 30 times the concentrations in sediments deposited in the 1880s. Changes in PAH concentrations over the last century are much greater in sediments deposited close to probable sources of PAHs in the industrialized bays. The decrease in concentrations of PAHs observed since the late 1950s may result from improvements in industrial practices and conversion from coal to cleaner-burning oil for home heating.

Metals also have natural sources (e.g., erosion of soils) that contribute to the measurable concentrations observed in the 1800s (Figure 55). Several metals (e.g., lead from auto exhaust) show increased concentrations over the last century, but again the concentrations have leveled off or decreased somewhat in recently deposited sediments. Concentrations of these contaminants will probably never be reduced to the levels observed before industrialization of Puget Sound.

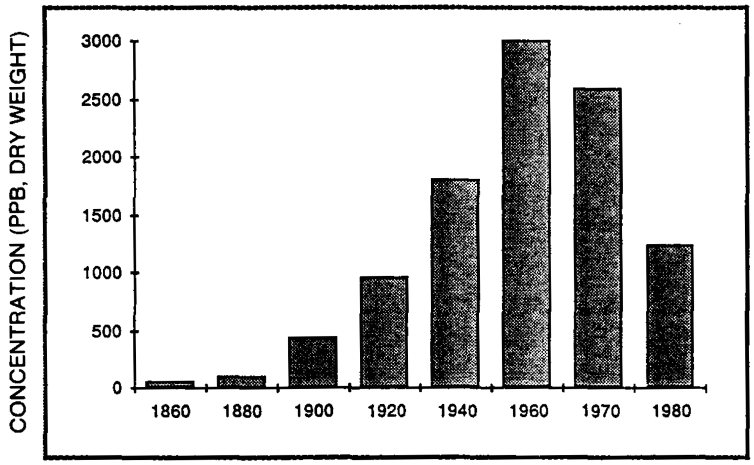
Accurate measurements of the concentrations of many toxic chemicals in the environment have been made only in the last several years. Because of this, it is difficult to assess trends in the levels of contamination for all but a few toxic chemicals. Some chemicals, such as PCBs and lead, have been subject to major efforts at control and show a trend of decreasing discharges and sediment concentrations in recent years. For other chemicals, such as phenols, the data are insufficient to draw firm conclusions. Some chemical levels may be getting worse. And, of course, new chemicals are entering the marketplace and eventually the Sound. No testing is done for these chemicals.

Transport and Transformation

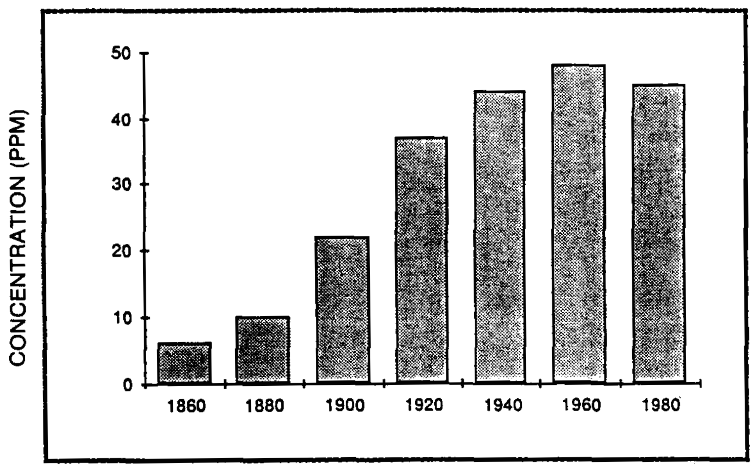
Contaminants that enter Puget Sound are transported to their final resting places, called sinks, where they accumulate. Chemical and physical properties of contaminants strongly influence how they are transported and where they eventually end up (their fate). The environmental behavior of contaminants is complex because contaminants (particularly trace metals) can occur in numerous forms with different chemical properties and because many different processes can act on a contaminant over time. Important environmental processes that govern the fate of different contaminants in the Sound are: the physical and chemical interactions of contaminants with seawater and the particles it contains; transportation of contaminants by moving water and particles; and chemical transformations of contaminants in seawater, sediments, and organisms. Figure 56 illustrates some of the more important and better understood pathways and sinks for contaminants in Puget Sound.



TOTAL PCB'S



COMBUSTION PAH'S



LEAD

Figure 55

HISTORY OF SEDIMENT CONTAMINATION BY PCB'S, PAH'S AND LEAD IN CENTRAL PUGET SOUND FROM 1860 TO 1980

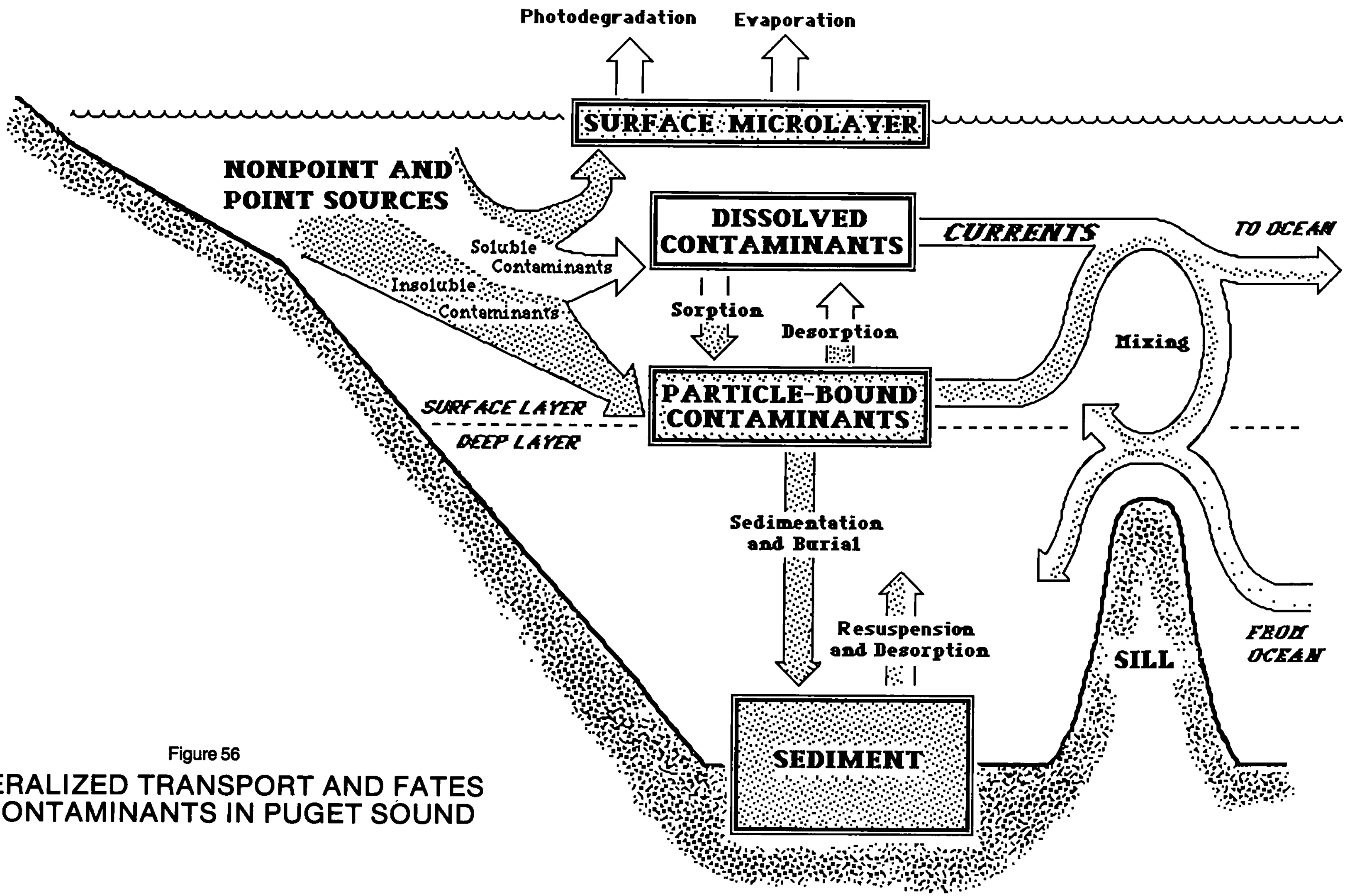


Figure 56

GENERALIZED TRANSPORT AND FATES OF CONTAMINANTS IN PUGET SOUND

Solubility

One of the most important factors affecting the fate of a contaminant entering the Sound is how easily it dissolves in seawater. The more soluble a contaminant, the longer it remains within the waters of the Sound where its fate is determined mainly by currents. As it enters the Sound, water containing dissolved contaminants is rapidly diluted by mixing and dispersed throughout the Sound. After circulating and recirculating, it travels into oceanic waters (Figures 15 and 16). Some of the more soluble contaminants are the nutrients in sewage effluent and phenolic compounds in wastes from pulp-and-paper mills. Dissolved contaminants can enter the Sound through rivers, surface runoff, municipal or industrial discharges, atmospheric precipitation, or the ocean.

Particle Binding

Some dissolved contaminants can chemically bind or adhere to particles by a process known as sorption. Sorption tends to occur on fine-grained sediments (silts or muds) rather than coarse, sandy sediments. Fine organic particles suspended in water, such as living or dead plankton and particulates from sewage, have a high sorption capacity, especially for dissolved organic contaminants. Trace metals can sorb onto very fine particles of iron and manganese oxide that form in well oxygenated water. Dissolved metals can combine with other dissolved inorganic substances to form insoluble particles that settle out of the water. Many of the contaminants that enter the Sound are poorly soluble and have a much greater affinity for particles (especially organic particles) than for water. Relatively insoluble contaminants such as PCBs and PAHs are predominantly associated with fine-grained particles that have a high content of organic matter. Bacteria in Puget Sound also adhere to organic particles as a source of nutrition.

Contaminants also enter Puget Sound in particle-bound form through erosion along rivers and shorelines. Metals such as nickel and chromium occur naturally in soils and can be transported on eroded particles. Particle-bound contaminants also enter the Sound as part of municipal and industrial waste, surface runoff, atmospheric particles (lead from automobile exhaust and PAHs from the combustion processes), and disposed dredged materials.

Particle Transport

The fates of contaminants bound to particles are very different than those of dissolved contaminants. Particles suspended in Puget Sound water are constantly settling under the force of gravity. Where they settle depends on their size and density and on the strength and direction of currents. Poorly soluble contaminants that attach to particles are transported by currents. Eventually they sink to the bottom and are not carried as far as those that are dissolved. Zooplankton can alter the dispersal rate of fine particles carrying contaminants by ingesting them and depositing them as larger fecal particles which settle more rapidly. Because contaminated sediment does not spread as far from its source as contaminated water does, the degradation it causes is more localized but more intense. Contaminants in sediments can be up to a thousand times more concentrated than those dissolved in the water. The result is the formation of hot spots of toxic sediments near sources of contamination.

The urbanized bays of Puget Sound are especially prone to becoming hot spots because several processes effectively trap particles and their associated contaminants within these bays. When fine, organically enriched particles in river water contact seawater, they tend to adhere to one another and settle more rapidly, a process known as flocculation. The typical estuarine flow pattern at river mouths, where a lower layer of saline water moves upstream, tends to prevent settling particles from being transported far from their riverine source. Sediments are often deposited in bays where prevailing currents are weak. In contrast, areas with rapid circulation, such as Admiralty Inlet or Dana Passage, are more likely to transport sediments than to allow them to settle.

Resuspension and Dissolution

Bottom sediment can be a source as well as a burial place of contaminants. For example, sediments and associated contaminants can be stirred up (resuspended) into overlying water by strong currents driven by wind, ship traffic (in shallow waterways), dredging operations, or even by organisms actively burrowing and feeding in the sediment. During resuspension, particle-bound contaminants can be transferred back into the dissolved state. Redissolution affects trace metals more than PCBs or PAHs.

Spills

In contrast to the steady chronic flow of low levels of contaminants from various sources around the Sound, large amounts have been spilled in small areas by occasional accidents or historical dumping practices. In such high concentrations the fate of the spilled contaminants may differ from the pattern described earlier.

Oil spills provide a good example of how physical processes affect the fates of contaminants. Oil is a complex mixture of many organic compounds. A small fraction of the compounds in crude oil will dissolve in water. The other compounds float on the water's surface, evaporate into the atmosphere (the lighter fractions), or clump into tar balls that sink to the bottom (the heavier fractions). Portions of all the fractions adhere to particles which eventually sink to the bottom. Spills of raw sewage follow a similar pattern: some "floatables" such as oil and grease rise to the surface, other components such as nutrients dissolve in the water, and the remaining insoluble fractions (including particles) eventually sink to the bottom. A PCB spill that occurred in the Duwamish River in 1974 provides another example of the behavior of spilled contaminants. The PCBs, which are poorly soluble and denser than water, sank to the bottom, pooled there, and mixed with the sediments.

SEA SURFACE MICROLAYER

Concentrations of trace metals and organic contaminants one hundred to 10,000 times greater than those in the underlying water column have been observed in a very thin (about 0.002 inches or 0.05 millimeters thick) layer at the water's surface called the sea surface microlayer. The high level of contaminants in the surface microlayer is related to the high level of dissolved organic matter that constitutes this layer. The organic matter is a complicated mixture of natural and sometimes synthetic substances that float on the surface like oil.

The sea surface microlayer receives fallout of contaminants from the air. Oil and grease in municipal sewage and industrial effluent can reach the microlayer, as do high numbers of bacteria. Organic and trace metal contaminants in the microlayer are susceptible to transfer to the atmosphere by evaporation. Organic contaminants in the microlayer also are susceptible to chemical changes and degradation caused by sunlight. The relative impact of contamination of the microlayer compared with sediments has not been well established.

BIOLOGICAL AND CHEMICAL PROCESSES

Biological processes complicate the fates of contaminants. Organisms can store contaminants and can transform and decompose them through metabolic processes (Figure 57). Biological transport and fate, like physical transport and fate, depend on chemical properties of contaminants such as their water solubility. The physiology of organisms also plays an important role. For example, if an organism takes up a contaminant but cannot break it down or eliminate it, it will accumulate the contaminant over time.

Bioaccumulation

The uptake and retention of chemical contaminants obtained from food, water, or sediments is called bioaccumulation. The compounds most readily bioaccumulated from water are those with the lowest water solubilities such as complex PAHs and PCBs. Since these compounds are highly soluble in fats and oils, they are readily stored in fatty tissues including the liver and fatty muscles. Contaminants can be bioaccumulated from both sediment and water. Bottom-dwelling organisms (such as worms and clams) that feed on sediment are particularly susceptible to this kind of uptake. In this way, bottom sediments, usually considered a sink for contaminants, can also be a source of contaminants to animals. The ability of organisms to accumulate contaminants from sediments is influenced by how strongly the contaminant is bound to the sediment. Bioaccumulation also occurs when contaminated organisms are eaten by another organism. This is a particularly critical process for animals that are higher on the food web such as fish and seals.

Biotransformation

The chemical alteration of a contaminant by an organism, called biotransformation, can sometimes make a contaminant more toxic; the complete breakdown of an organic compound to simple chemical compounds (e.g., water and carbon dioxide) is called biodegradation. Trace metals are chemical elements and cannot be broken down, but many metals (such as mercury, lead, and arsenic) can be biotransformed into more complex compounds.

Estuarine organisms have widely varying degrees of biological complexity (from bacteria to marine mammals) and widely varying abilities to chemically transform contaminants. Bacteria, which are widely distributed in the water column and in sediments, are generally effective at transforming and degrading contaminants. They can degrade some of the more simple PAHs and PCBs but are largely ineffective at transforming or degrading the more complex forms. Bacteria cannot degrade metals, but they can transform some metals by bonding them to small organic molecules. The resulting organometallic (organic and metallic) compounds can be far more toxic and easy to bioaccumulate than the metals in elemental form (especially in the case of mercury).

Higher organisms also have some ability to chemically transform contaminants. For example, fish can biotransform PAHs, whereas clams and oysters have less ability to biotransform PAHs and thus have a greater tendency to bioaccumulate them. Fish, clams, and other marine organisms have a very limited ability to transform or degrade PCBs. Thus, PCBs, which are readily taken up, tend to accumulate in these animals over time.

In fish and mammals the liver is the primary site of biotransformation of organic compounds such as PAHs. These contaminants are biotransformed by enzymes that make the compounds more water soluble and less fat soluble. Bivalve shellfish (clams, mussels, and oysters) and crustaceans (crabs and shrimp) are not as efficient as fish at eliminating PAHs. Because these compounds are rapidly transformed, they cannot be detected in the organism even when the exposure has been great and damage has occurred. Organic and metal contaminants can also be made more soluble when they are chemically bonded to proteins and other natural components of the tissues, making them easier to excrete. However, chemical transformation can either increase or decrease the toxicity of the contaminant to an organism. For example, some biotransformed PAHs are more toxic to fish than unaltered PAHs.

Organisms have several ways of releasing contaminants and their transformed byproducts back into the environment. Bottom-dwelling organisms that feed on sediments such as worms release sediment as fecal material. Contaminants that are not bioaccumulated are released to surface sediments in this form or become undetectable. Biotransformed contaminants such as PAHs transformed by fish can be released into the water through the digestive system. Biotransformed compounds released into the environment are seldom measured in environmental studies because they are numerous and difficult to detect in the laboratory.

CONTAMINATION OF ORGANISMS

This section reviews what is known about the incidence of chemical contamination in several marine organisms and the incidence of liver lesions in English sole in Puget Sound. The following sections discuss how these conditions can be related to possible causes and what can be said about the implications of contamination for human health in the Puget Sound area.

Heavy contamination is often seen after a sudden, concentrated release of a contaminant, such as a spill. In such cases many of the causes and effects of contamination are obvious. Severe effects including widespread deaths of organisms were apparent in the case of historical pulp mill discharges and were seen again recently following the ARCO Anchorage oil tanker accident at Port Angeles in December 1985. Conspicuous zones of mortality and community disturbance also can be seen today in the immediate vicinity of some point source discharges and CSOs and in areas where habitat is altered or destroyed by dredging and filling. Fish kills are observed regularly, following oxygen depletion caused by decay of both natural phytoplankton blooms (in such locations as Lynch Cove at the head of Hood Canal) and organic matter from human sources. Human-induced fish kills were much more numerous in the past when open water dumping of organic waste (such as waste from fish processors) was more widespread. Events that cause obvious short-term impacts may also set the stage for longer-term effects that are harder to

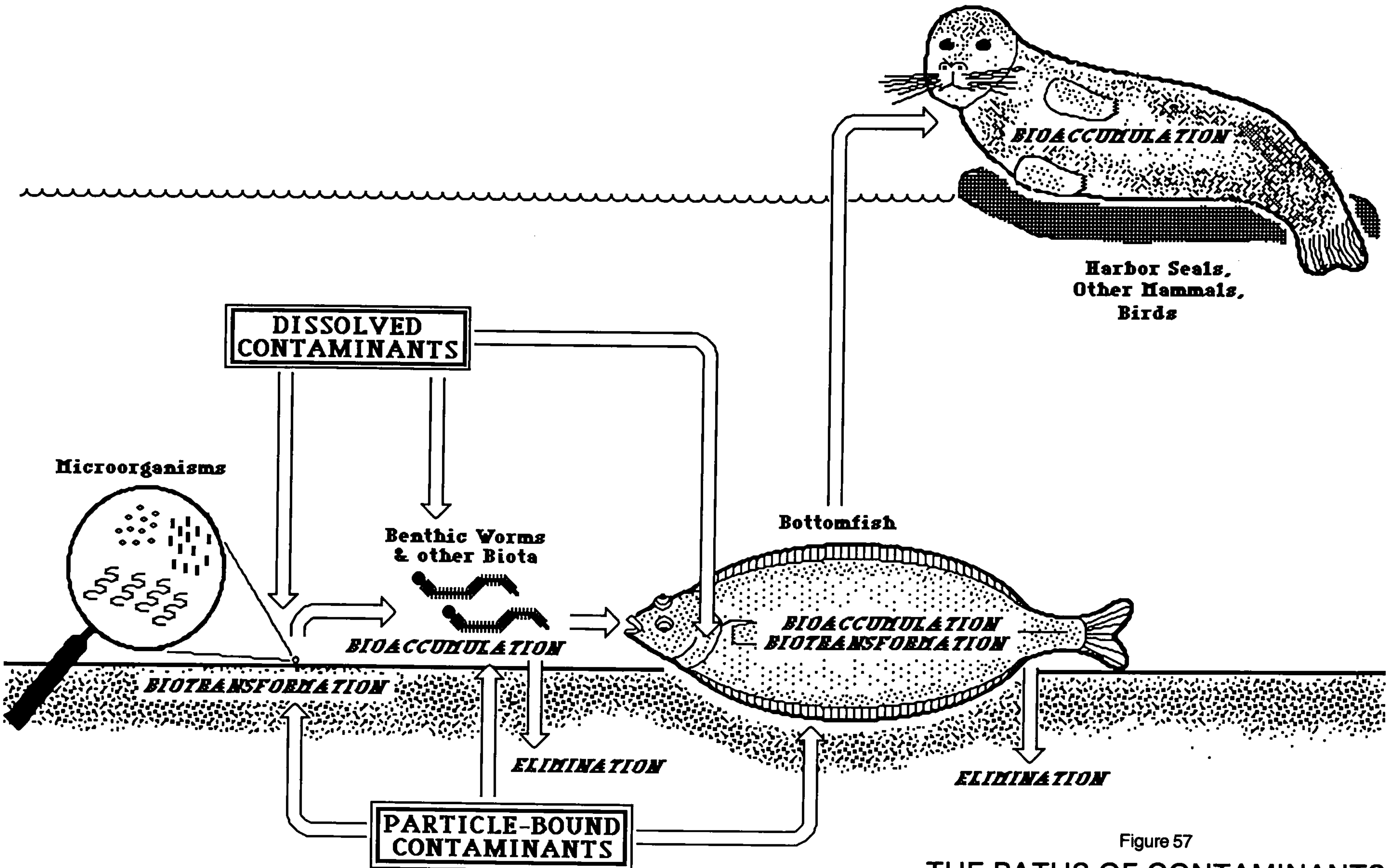
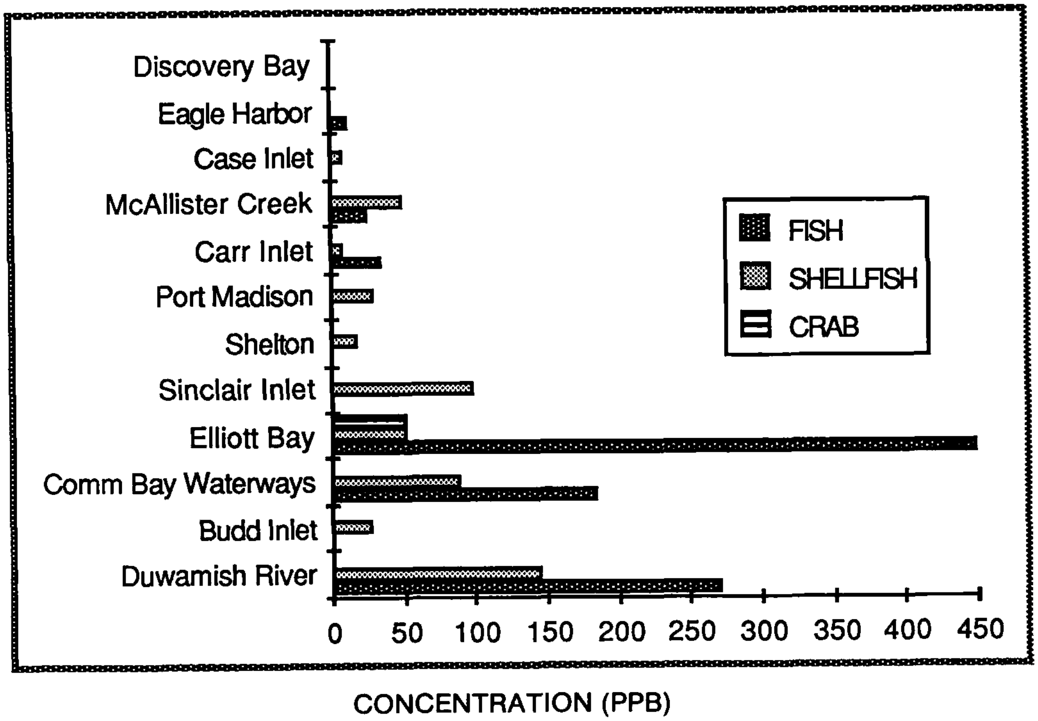


Figure 57
THE PATHS OF CONTAMINANTS THROUGH ORGANISMS



FISH: English sole muscle (all locations except Duwamish River and McAllister Creek)
Starry flounder muscle (Duwamish River and McAllister Creek)

SHELLFISH: Clams (whole soft body)
Mussels (whole soft body)

CRAB: Muscle tissue only

Figure 58

GEOGRAPHIC DISTRIBUTION OF PCBs IN SELECTED FISH, SHELLFISH AND CRABS OF PUGET SOUND

confirm. For example, past PCB releases in the Duwamish River may still be contributing to the uptake of PCBs by fish and other organisms.

Accumulation in Organisms

Residues of organic contaminants (e.g., PCBs, DDT, and PAHs) have accumulated to a greater degree than metals in the body tissues of Puget Sound organisms. Excessive bioaccumulation of toxic substances is observed mainly in organisms found in the industrialized urban areas of the Sound. The geographic pattern of bioaccumulation is illustrated for PCBs and PAHs in Figures 58 and 59. The length of each bar shows the approximate concentration of contaminants in muscle tissue of fish and crabs or in whole clams or mussels. These figures are rough averages of data collected since 1974 and are not a comprehensive synthesis.

The dominant organic contaminants observed in Puget Sound organisms include certain polynuclear aromatic hydrocarbons (PAHs), halogenated hydrocarbons (e.g., PCBs, and DDT and its breakdown products), and another class of industrial chemicals found in plastics called phthalate esters. PCBs and DDT are the most frequently reported compounds in higher organisms (fish, birds, and marine mammals).

PCBs are found in various tissues of the species examined in Puget Sound, although concentrations in liver tissues are consistently higher than those in muscle regardless of the degree of contamination of the organism. Atmospheric sources, long-distance transport in water, and the high capacity for bioaccumulation of PCBs probably account for the widespread PCB contamination in Puget Sound. Concentrations of PCBs are somewhat higher in invertebrates and bottom and near-bottom fish collected from the urban areas of Puget Sound than from non-urban areas (Figures 58 and 60). The 1974 PCB spill in the Duwamish Waterway is one likely source of this high contamination (Figure 58). In addition, historic uses of PCBs by utilities have been identified in urbanized areas.

Concentrations of PCBs in the tissues of marine birds are high in some Puget Sound locations compared to such concentrations in many other areas of the world. However, only limited numbers of herons, pigeon guillemots, and gulls have been analyzed, and further monitoring is required to determine whether a problem exists. PCB concentrations in blubber from harbor seals collected in southern Puget Sound have ranged up to 750 ppm (wet weight) and are among the highest found worldwide. The average PCB concentration in all blubber samples from southern Puget Sound (110 ppm wet weight) was six times the average of samples from Hood Canal, and 10 times the average of samples from northern Puget Sound.

In fish, elevated PAH levels are observed mainly in liver, not in muscle tissue. Elevated PAH concentrations are found in fish and shellfish in the Commencement Bay Waterways (especially Milwaukee and City Waterways), Elliott Bay and the Duwamish Waterways, Sinclair Inlet, Eagle Harbor, and the area around the Mukilteo ferry dock (Figure 59). The Washington Department of Ecology is currently investigating the Wyckoff lumber treating facility as a probable source of creosote (PAH) in Eagle Harbor (Bainbridge Island). Discharges or spills of petroleum and runoff from automobiles are probably

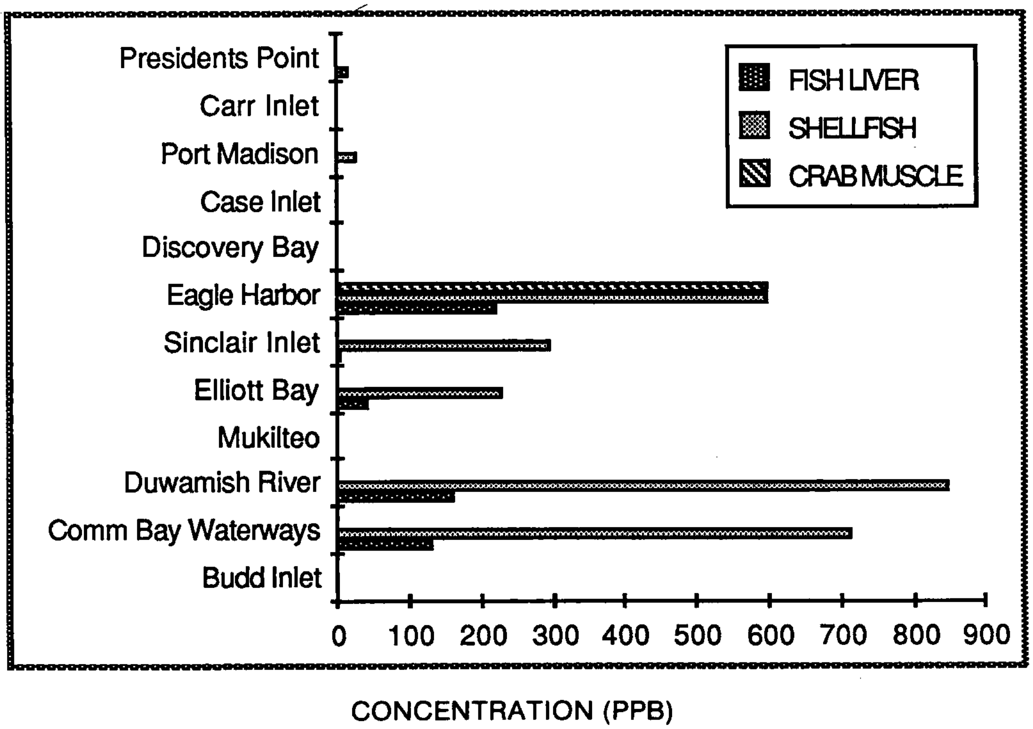


Figure 59

GEOGRAPHIC DISTRIBUTION OF PAHs IN FISH, SHELLFISH AND CRAB OF PUGET SOUND

(Reference: Malins et al., 198l, 1985; Gahler et al., 1982; Yake et al., 1984; Tetra Tech, 1985)

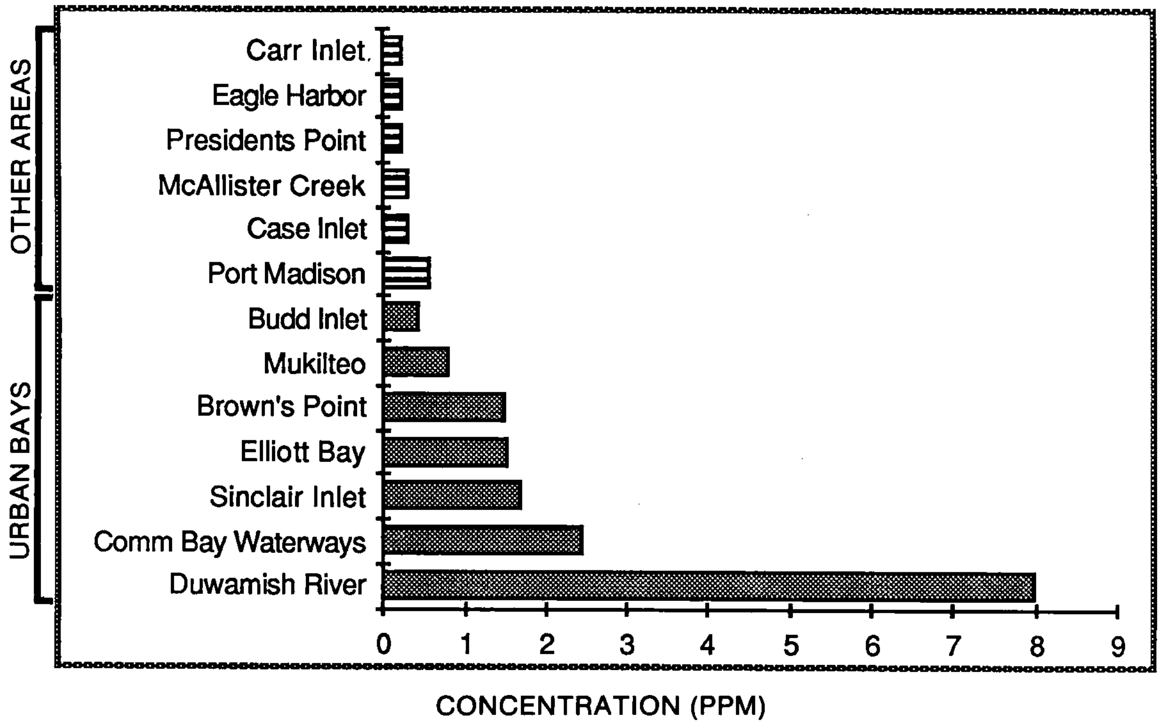


Figure 60

GEOGRAPHIC DISTRIBUTION OF PCB CONCENTRATION IN ENGLISH SOLE LIVER OF PUGET SOUND

(Reference: Malins et al., 1980, 1985
Tetra Tech, 1985)

major sources of PAH contamination in the Commencement Bay Waterways, Elliott Bay, and the Duwamish River. Jet fuel spills from the Defense Department Fuel Storage Facility are the likely source of PAHs at Mukilteo. In fish, elevated PAH levels are observed mainly in the liver, not in muscle tissue.

There are high concentrations of toxic metals such as mercury, lead, and copper in the tissues of bivalve shellfish and crustaceans, fish livers, and birds taken from industrialized areas of Puget Sound (e.g., Duwamish River, Commencement Bay Waterways and Ruston shoreline, Bellingham Bay, and Inner Everett Harbor). Concentrations are much lower in remote reference areas (e.g., Carr Inlet and Discovery Bay). Higher levels of metals in the tissues of marine organisms generally are found in areas where sediment contamination is more severe than it is in other areas. For example, bivalves (mussels) showed elevated concentrations of mercury near a chloralkali plant located on Bellingham Bay. Elevated concentrations of copper, lead, and zinc are found near the former American Smelting and Refining Company (ASARCO) copper refinery on Commencement Bay. In fact, levels of contamination by metals are more uniform around the Sound than levels of contamination by organic compounds.

Fish generally do not accumulate metals in muscle tissue even in areas of heavy contamination in the sediments. The exception is mercury which in the mid-1970s was shown to be excessively high (greater than one ppm) in most samples of dogfish from Elliott and Commencement Bays, Port Susan, Hood Canal, and Port Townsend. Dogfish sharks appear to concentrate mercury. The limited data available for salmon do not indicate excessive accumulation of metals in edible muscle tissue. Metals in the liver and kidneys of harbor seals from southern Puget Sound are generally not exceptionally high aside from mercury in a few samples.

Most data on bioaccumulation in Puget Sound are too limited to establish temporal trends. Nevertheless, concentrations of PCBs in bottomfish from the Duwamish River clearly decreased between 1972 and 1979 (Figure 61). Mercury in mussels of Bellingham Bay (near the chloralkali plant) decreased by an order of magnitude from 1970 to 1978.

Liver Abnormalities in English Sole

Over the past 10 years, a variety of liver abnormalities have been found in English sole and other finfish species from a number of areas throughout Puget Sound. Lower rates of liver abnormalities also have been found in rock sole and Pacific staghorn sculpin from Puget Sound. Liver abnormalities are rare in the other species examined thus far in Puget Sound.

There is a strong association between liver abnormalities in English sole and chemical contamination of sediments, but there are a variety of other possible causes of the observed abnormalities including nutritional imbalance, genetic disorders, infections by microorganisms, and a variety of natural environmental stresses such as low salinity and high temperature. There is also a possibility that the sea surface microlayer may play a role because the eggs of English sole float at the surface of the water and may come into contact with contaminants in the microlayer. It is not known whether these liver abnormalities affect the health of individual fish or the status of populations.

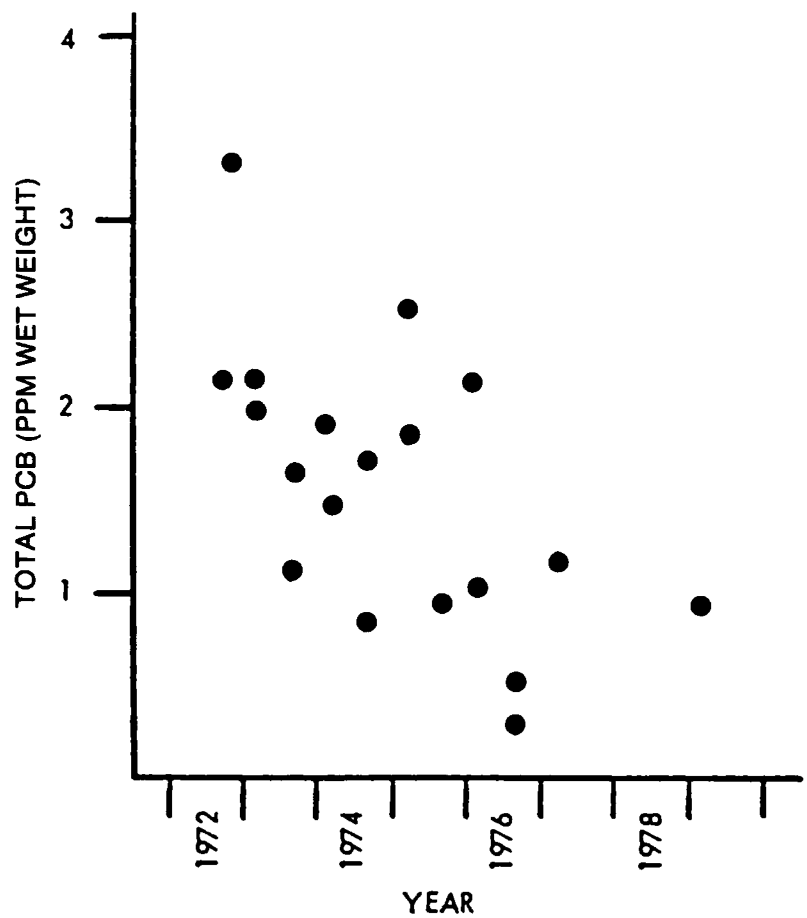


Figure 61

TEMPORAL TRENDS OF PCB'S IN WHOLE ENGLISH SOLE, PACIFIC STAGHORN SCULPIN AND STARRY FLOUNDER OF THE DUWAMISH ESTUARY

The distributions of two major kinds of liver abnormalities in English sole, tumors and pre-tumor conditions, are presented in Figure 62. Tumors may be benign or malignant, whereas pre-tumors are clusters of altered cells that occur with and may be precursors to tumors. Laboratories have induced both kinds of tumors in mammals and fish by exposing them to toxic chemicals. Animals that developed tumors in the laboratory generally developed pre-tumors first, but all pre-tumors did not necessarily become tumors.

Tumors are found in about five percent of English sole from urbanized areas of Puget Sound, while pre-tumor conditions occur in about 13 percent. The corresponding figures for non-urban areas are approximately one and two percent, respectively. The highest occurances of both abnormalities are in Eagle Harbor (27 percent for pre-tumors and 44 percent for tumors).

Little is known about whether the prevalence of liver abnormalities in Puget Sound English sole is increasing or decreasing. There were no studies of these conditions before the mid-1970s, so no historical data base exists. In addition, many recent studies have surveyed new areas rather than returning to previously sampled sites. However, regular surveys of several Puget Sound stations were conducted between 1979 and 1983. In Commencement Bay and Sinclair Inlet, studies conducted between 1979 and 1983 (Figure 63) could detect no consistent increase or decrease in the prevalence of tumors or pre-tumor conditions. In Elliott Bay, the results suggest that the prevalence of tumors and pre-tumor conditions increased over the four-year period (Figure 63). (This may in part be explained if the recent samples included older fish which have been exposed to toxic chemicals for a long period of years.)

Cause-and-Effect Relationships

One of the most important and difficult tasks confronted by environmental scientists is determining the direct cause or causes of a biological condition observed in the environment or the direct consequences of a particular type and degree of contamination. Cause-and-effect relationships are difficult to prove because organisms are continually exposed to a wide range of environmental stresses, natural and otherwise, in addition to chemical contamination. These stresses include changes in water temperature and salinity, variations in food quality and availability, predation and competition, and disease. Commercial species are also subject to overharvesting. Environmental stresses act singly or in combination to affect organisms in a myriad of ways. For example, chemical contaminants often combine to make complex mixtures, making it difficult to single out the effects of a specific chemical or disease-causing agent. Finally, because only a limited number of chemicals can be routinely measured in the environment, the real cause of any given biological effect may be overlooked.

A practical approach to studying cause-and-effect relationships is to integrate data taken from Puget Sound with data generated by laboratory experiments. First, data are collected in the field to describe existing contamination and biological conditions. Samples are collected at a site of suspected or known contamination (or impacts) and at a relatively clean reference site.

The second step is to determine whether there is a statistical relation between chemical contamination and biological conditions observed in the field data.

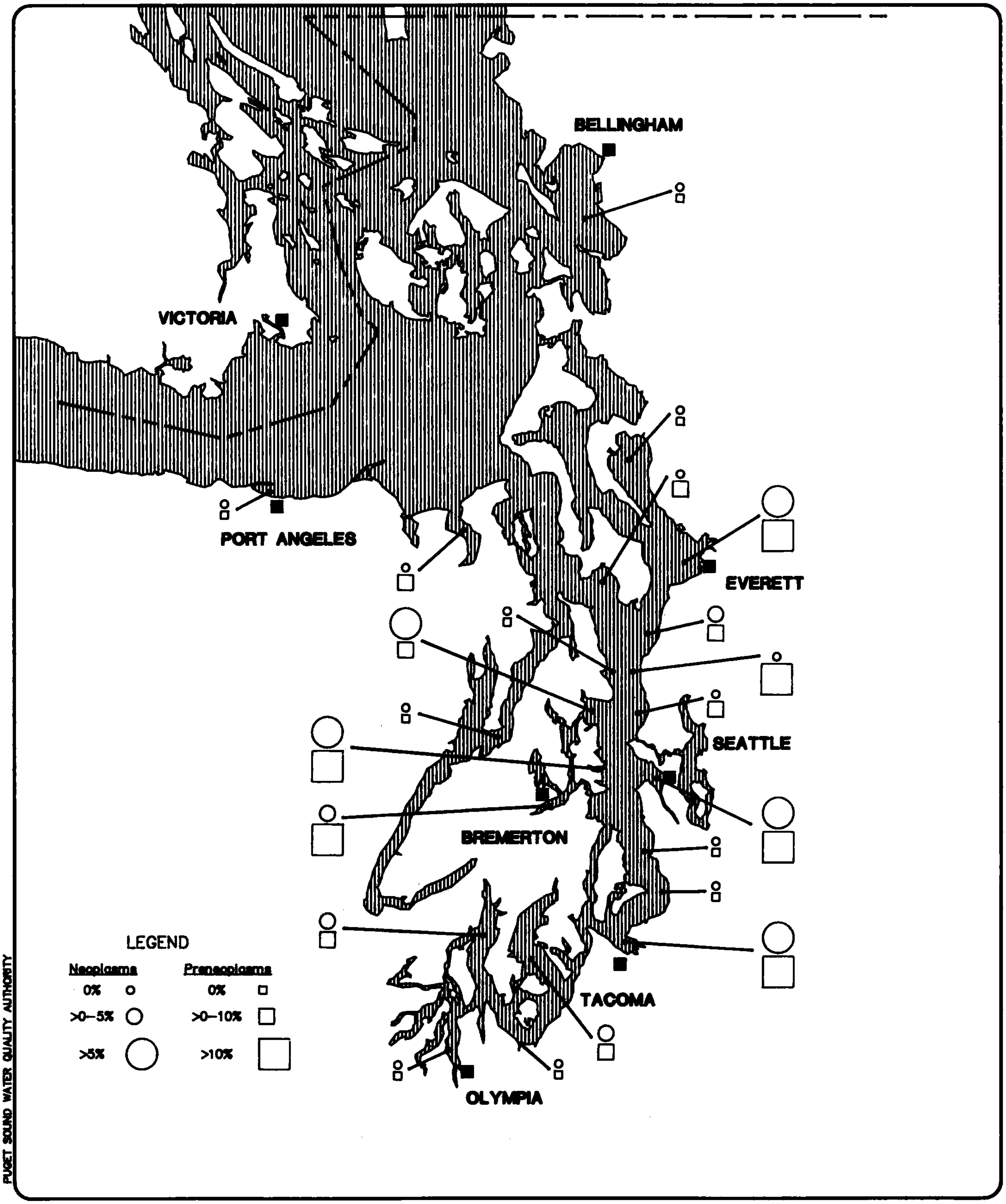
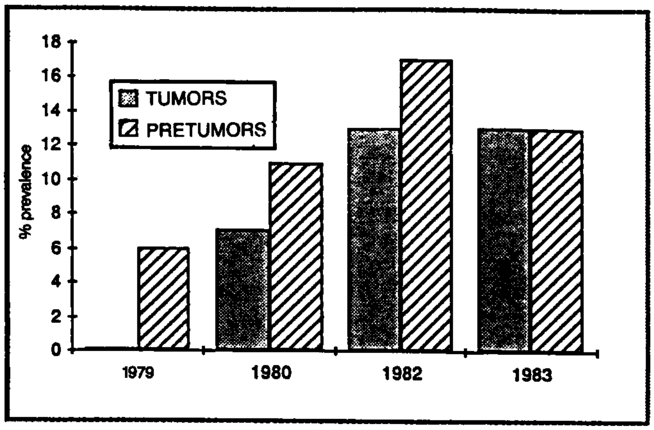
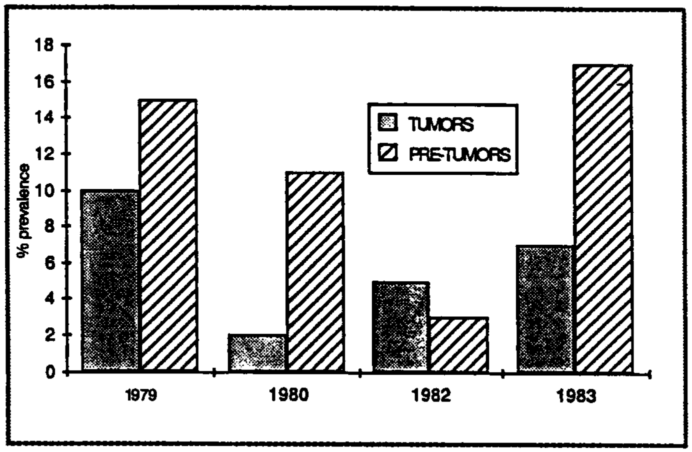


Figure 62

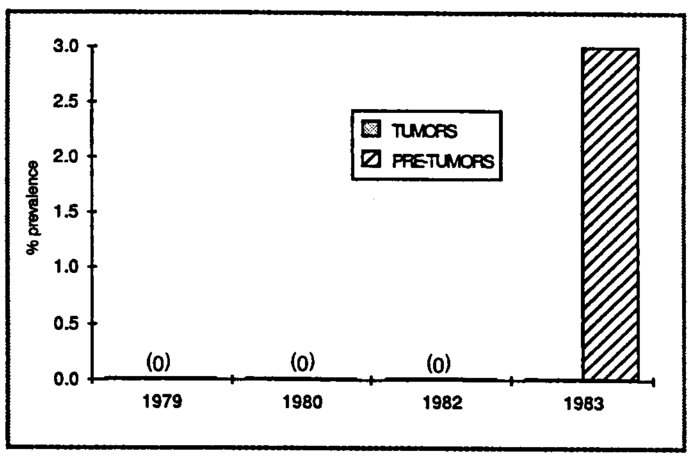
TUMORS (NEOPLASMS) AND PRE-TUMORS (PRE-NEOPLASMS) IN ENGLISH SOLE OF PUGET SOUND



ELLIOTT BAY
(4 Stations)



COMMENCEMENT BAY
(2 Stations)



SINCLAIR INLET
(1 Station)

Figure 63

TEMPORAL TRENDS OF LIVER TUMORS
IN ENGLISH SOLE
(SUMMER ONLY)

An increase in a biological effect (for instance, liver tumors) that seems to correspond to an increase in concentration of a given contaminant (for instance, PAH) may turn out to be statistically insignificant, meaning the correspondence could have occurred by chance. Careful studies are necessary to demonstrate a statistical relationship.

The final step in defining cause-effect relationships is to conduct laboratory experiments to try to reproduce the condition observed in the field and to help support any statistical correlations between biological effects and contaminants that were revealed by field studies. In the laboratory, individual chemicals can be tested to determine whether relationships defined by field data are dependent on one contaminant or mixture or on a variable not sampled.

One method of estimating the toxicity of a contaminant or mixture to biota is to expose individuals of a contamination-sensitive species to contaminated sediment or water under controlled laboratory conditions and measure their response. This procedure is called a bioassay and has been conducted on sediment and water samples collected from many areas of Puget Sound.

The most common test species for sediment bioassays in Puget Sound has been the amphipod crustacean Rhepoxynius abronius. These small shrimp-like animals (sometimes called sand fleas) live near the sediment surface in many parts of Puget Sound. They are important prey for many types of fish and are relatively sensitive to contamination. The amphipod bioassay measures mortality in a test population of Rhepoxynius abronius following a 10-day exposure to test sediment.

The generalized results of amphipod bioassays conducted on sediments from over 300 stations throughout Puget Sound are presented in Figure 64. In general, very high maximum mortalities (greater than 50 percent of the 20 organisms used per test) were found at sites with high concentrations of toxic chemicals in the surface sediments in the major urban bays (i.e., Commencement Bay, Elliott Bay, Port Gardner, and Bellingham Bay) and in Eagle Harbor.

In addition to the amphipod mortality bioassay, a variety of other tests have been conducted on Puget Sound water and sediments. They include bioassays based on oyster larvae mortalities and abnormalities, genetic abnormalities in fish cells, respiration changes in oligochaetes (small marine worms), and changes in bacterial luminescence. In general, these additional bioassays have shown trends similar to those of the amphipod mortality bioassay.

A summary of the general knowledge of cause-effect relationships in Puget Sound is given in Table 18. Establishment of cause-effect relationships is a science in itself and is still very much in its infancy. As a consequence, many of the subtle adverse biological conditions such as liver abnormalities and changes in benthic communities have not been clearly linked to specific contaminants. However, evidence from field sampling can be used to strongly

TABLE 18: BIOLOGICAL CONDITIONS: CAUSES AND EFFECTS IN PUGET SOUND

Condition	Possible Causes	Possible Effects
Histopathological Abnormalities in Bottomfish and Other Organisms	Toxic chemicals in water, sediment, or food; dietary deficiencies; pathogens; natural environmental stress	Condition may improve or worsen in response to changes in pollutant loading (or other environmental stresses). Conceivably stresses worsen enough to threaten entire populations.
Benthic Community Changes	Toxic chemicals in water, sediment, or food; organic enrichment; habitat alteration	Condition may improve or worsen in response to changes in pollutant loading, organic enrichment, or habitat alteration practices. Drastic adverse changes in bottom-dwellers could affect abundance of predators (bottomfish, for example).
Chemically Contaminated Tissue	Toxic chemicals in water, sediment, and food	Tissue levels may change in response to changes in pollutant loading. Changes in tissue levels could result in the removal of seafood consumption warnings or posting of new warnings, or, at worst, closure of a commercial or recreational fishery.
Bacterial Contamination of Shellfish	Bacterial contamination of water	A decrease in bacterial loading could result in the reopening of many commercial harvest areas. An increase in loading may force closure of additional commercial areas and possibly recreational areas.
Plankton Blooms	Nutrient and freshwater input, suspended solids, dissolved copper, decreased natural inhibitory mechanisms	Increase in bloom frequency by PSP organism could cause closure of additional recreational shellfish harvest areas and possibly increased human health risk. No human activity has been directly implicated as a cause of this condition.
Fish Kills	Low dissolved oxygen, chemical spills, liquid manure (and sewage) spills, blooms	Reductions in the frequency of all harmful spills, quick response, cleanup, and containment would reduce the adverse effects of spills. It is not known to what extent (if at all) current human activities contribute to low dissolved oxygen Sound-wide. Certain areas would benefit from a reduction in BOD (Budd Inlet).
Declining Fish Stock	Overfishing, chemical contamination, natural phenomena (e.g., El Nino)	A reduction in fishing pressure and pollutant loading may result in fish population recoveries. However, causes of this condition are very poorly understood for Puget Sound.
Possible Reproductive Failure in Harbor Seals	Toxic chemicals, possibly PCBs, in food	A reduction in loading (already underway) may reduce PCB tissue levels in food sources, and consequently improve reproductive success of both species. A decline in reproductive success could threaten some Puget Sound populations.

correlate adverse biological conditions to certain areas that are heavily contaminated and to suggest further laboratory experiments.

Our present inability to prove cause and effect links does not mean that Puget Sound is not contaminated. The presence of liver lesions in English sole, the high bioassay mortalities and the depressed or totally absent bottom-dwelling communities in areas with relatively high sediment contamination levels clearly demonstrate that excessive chemical contamination exists in Puget Sound. If we wait until we have widespread mortalities in marine organisms to prove damage, then Puget Sound will surely be severely damaged.

POTENTIAL HUMAN HEALTH RISKS

RISKS DUE TO CHEMICAL CONTAMINATION

Direct contact with chemically contaminated water and sediments is not suspected of causing human health problems in Puget Sound, even in industrialized bays. (However, the extent of this potential problem is unknown.) The greatest potential for human health effects from chemical contamination of Puget Sound is contaminated seafood. The possibility that heavy consumption of highly contaminated seafood for a period of years could pose a human health risk has prompted several recent studies of seafood catch and consumption patterns.

Although human health risks from chemical contamination of seafood are well documented in other locations, there have been few studies that address risks from the levels of contamination found in the Puget Sound basin. Scientists are still unable to accurately predict the numerical rates of cancer (or other health effects) caused by human consumption of single or multiple chemicals in fish. However, we can make qualitative guesses about the relative health risks of eating seafood from different locations in the Sound by looking at one contaminant at a time. If cancer incidence is directly proportional to intake of a certain chemical (an assumption accepted by most researchers), then fish that have higher concentrations of that chemical will carry a greater human cancer risk when eaten. Thus, the relative human health risk due to that chemical can be estimated from the geographic distribution of tissue contamination (Figures 58 and 59). This approach is more difficult to apply to the risk of eating fish which contains multiple contaminants.

PCBs and PAHs, both suspected carcinogens, have been identified as the primary problem chemicals in bottomfish and shellfish from contaminated bays. In general, levels of metals in Puget Sound seafoods do not pose risks to human health. (Because PAHs are concentrated in the liver rather than in fish muscle and PCBs are concentrated in fish muscle, PCBs pose the greater risk to human health.) The risk to human health of eating PCB-contaminated bottomfish (e.g., English sole) from Commencement Bay or the Elliott Bay/ Duwamish River Waterways over a 70-year lifetime is estimated to be five to 30 times greater than the corresponding risk of eating bottomfish from Carr Inlet. The consumption of 30 pounds of clams per year per person from Eagle Harbor (the highest rate estimated for recreational harvesters) would result in an intake of the suspected human carcinogenic PAH benzo(a)pyrene 0.35 to 3.5 times that of the average diet. However, no risk assessment has been

conducted for other cancer-causing PAH compounds known to be present in the clams and crabs of Eagle Harbor.

County and state health agencies have issued public advisories to limit consumption of fish and shellfish from the Commencement Bay waterways, inner Elliott Bay and the lower Duwamish River, Eagle Harbor, inner Everett Harbor, Budd Inlet, and the Mukilteo fishing pier. Despite the concern over heavy consumption of bottomfish and shellfish from contaminated areas of Puget Sound, little is known about contamination of salmon. Limited analyses of salmon muscle tissue by Metro and NOAA showed PCB concentrations (140 to 1,350 ppb) comparable to those in bottomfish, but no conclusions have been drawn at this time.

The U.S. Food and Drug Administration (FDA) has established guidelines on concentrations of mercury and 13 organic compounds in fishery products which apply to interstate commerce. The FDA reported that no Puget Sound fisheries have been closed because of contamination in excess of these guidelines. As shown in the current scientific literature (since 1980), only a small fraction of edible tissue samples from marine organisms of Puget Sound exceeded the PCB guidelines of two ppm. Guidelines for other contaminants have not been exceeded except for mercury in samples of dogfish. Older data indicated that one hundred percent of the from Elliott Bay and 97 percent of those from Commencement Bay dogfish exceeded the FDA standard of one ppm mercury. In addition, the majority of dogfish samples from all Puget Sound areas including Hood Canal (which is considered to be rather clean) exceeded the FDA guideline.

Existing information is insufficient to establish temporal trends in human health risk associated with chemically contaminated seafood.

Despite this relative risk analysis, two important questions remain: what is the absolute risk to the exposed population, i.e., the number of new cancers resulting from chemical contamination in the human population with a regular diet (e.g., less than one meal/week) of seafood from Puget Sound? and what is an acceptable or tolerable risk?

Science alone cannot provide an answer to these questions, especially the second one. Agency policy guided by public discussion must establish guidelines for interpreting risk estimates and determining how high a risk warrants expenditure of public resources to reduce the risk.

RISKS DUE TO CONTAMINATION BY BACTERIA AND VIRUSES

Bacterial and viral contamination of water and shellfish pose a well-documented public health risk. Swimming in, or consuming raw or undercooked shellfish from, water contaminated with certain bacteria and viruses can result in gastroenteritis, nausea, diarrhea, typhoid fever, cholera, and hepatitis.

The state of Washington has set standards for water quality and commercial shellfish based on concentrations of fecal coliform bacteria. These bacteria are normally harmless and live in the gut of warm-blooded animals such as humans, cattle, birds, cats, and dogs. Fecal coliform bacteria are measured in water and shellfish tissue because they often indicate that contamination by

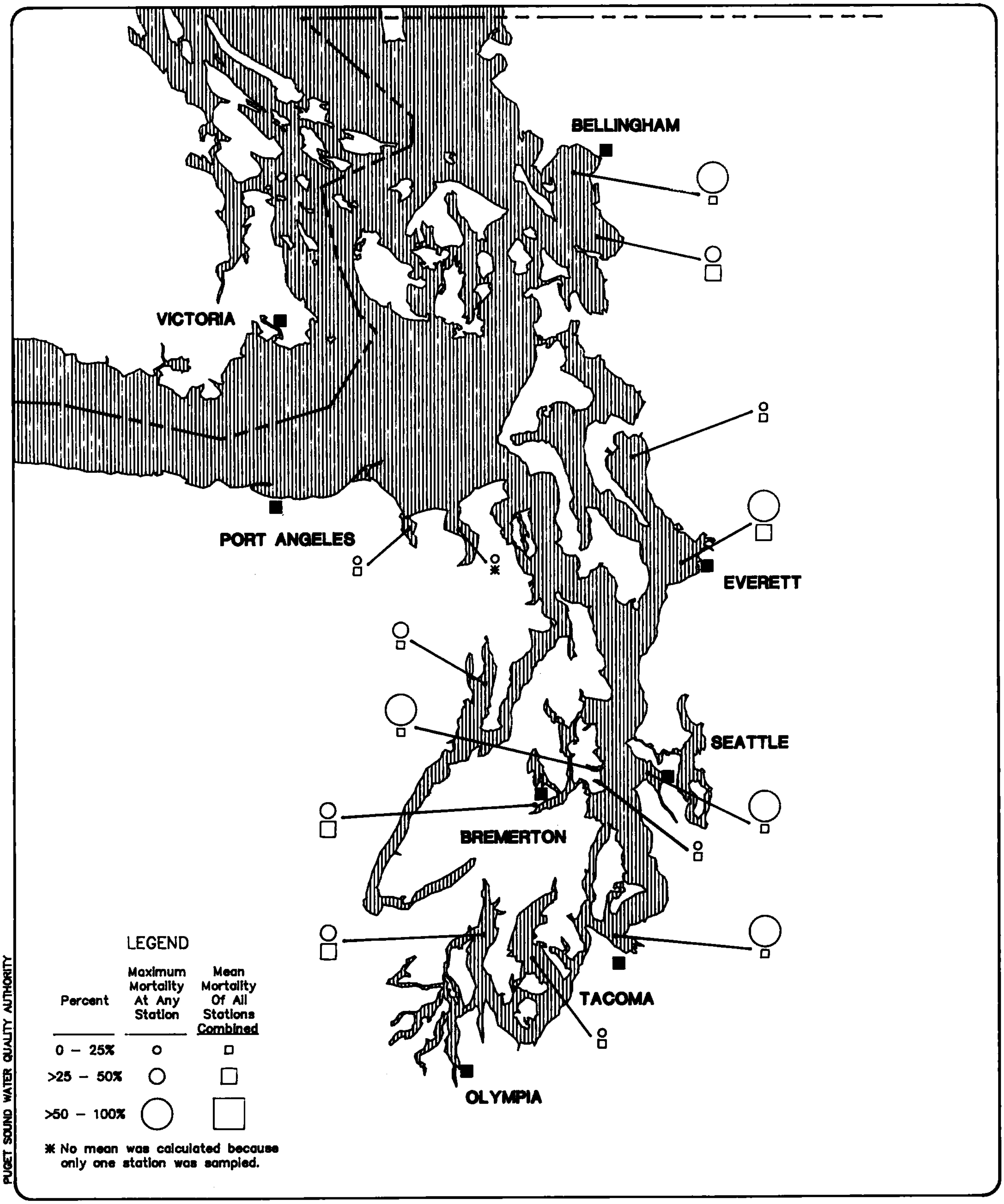
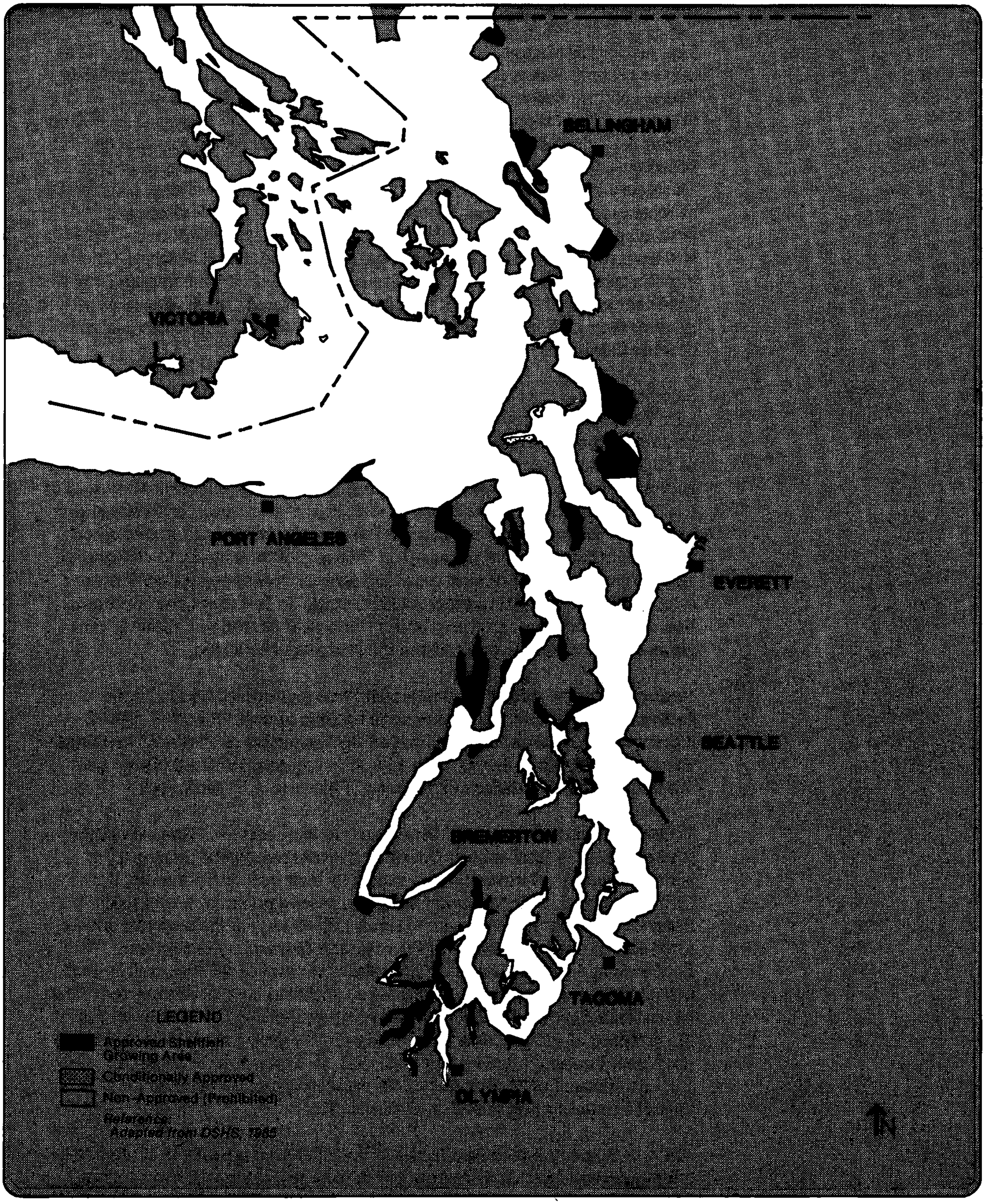


Figure 64

AMPHIPOD MORTALITY FROM SEDIMENT BIOASSAYS IN PUGET SOUND



PUGET SOUND WATER QUALITY AUTHORITY

Figure 65

STATUS OF COMMERCIAL SHELLFISH AREAS IN PUGET SOUND

fecal matter has occurred and that other potentially disease-causing organisms may be present. Areas used for the commercial harvest of shellfish are closed if fecal coliform bacteria are detected in concentrations in excess of 230 organisms/100 g (about 3-1/2 ounces) of shellfish tissue or 14 organisms/100 ml (about 3-1/2 fluid ounces) of the overlying water. The system for detecting possible bacterial contamination in Puget Sound is far from comprehensive. The state's shellfish inspection program does not routinely monitor commercial or recreational shellfish beds for bacterial contamination. Monitoring is initiated only when and where a contamination problem is suspected. There also is no routine monitoring of bacterial levels at swimming beaches. Once a monitored area has been decertified for commercial shellfish harvesting due to fecal coliform contamination, it is no longer monitored. Metro does routinely monitor fecal coliform levels near several sewage outfalls and closes swimming beaches in the area of raw sewage spills.

Since 1982, six areas previously certified for commercial shellfish harvesting have been closed to commercial oystering due to high levels of bacterial contamination. In addition, extensive areas (such as the entire eastern shore of Puget Sound from Everett to Tacoma) are closed to all commercial shellfish harvesting because of the number of potential sources of contamination such as treatment plant outfalls and urban runoff (Figure 65). Levels of fecal coliform bacteria in the water near urban areas frequently exceed water quality criteria for commercial shellfish growing areas. Because of their ability to concentrate microorganisms, shellfish near urban areas or sources of contamination also often exceed criteria for commercial harvesting. In one study, the concentration of fecal coliform bacteria in butter clams near Seattle was about 60 times greater than that in the water where the clams were collected.

Research outside of Puget Sound has shown a high correlation between gastrointestinal illness and enterococcal bacteria in water (another type of digestive tract bacteria) and has implied that swimmers are "at risk" in marine waters that contain as few as 10 enterococcal organisms/100 ml. There are few data on the abundance of enterococcal bacteria in Puget Sound.

Viruses are generally present where there are fecal bacteria. Enteric viruses (those present in fecal matter) can cause diseases in humans ranging from polio to hepatitis. Viruses have an extremely high infection potential; thus, their presence, in even the tiniest amounts, poses a potential health risk. Enteric viruses have been shown to survive up to 130 days in seawater and up to 90 days in oysters. Outside of Puget Sound (particulary in southern California and on the East Coast), hundreds of cases of shellfish-transmitted hepatitis (from eating raw or undercooked shellfish) have been reported. Few laboratories have the facilities for testing either shellfish tissue or water for the presence of enteric viruses, and commercially grown shellfish are currently not tested for these organisms in Puget Sound. Instead, fecal coliform bacteria are used as an indicator of the presence of fecal matter which is assumed to pose a risk of pathogenic infection.

Areas of Puget Sound most affected by bacterial (and possibly viral) contamination generally coincide with areas where there are sewage treatment plant outfalls (for example, Budd Inlet) and/or urban runoff, runoff from agricultural land, failing septic systems, or discharges from boats (for example, Henderson

Inlet, Eld Inlet, Burley Lagoon, Totten Inlet, Skookum Inlet, and Little Skookum Inlet). Areas in which contamination could be increasing due to development include Eld Inlet, Henderson Inlet, North Cove Inlet (Case Inlet), most of Hood Canal, Liberty Bay, and Penn Cove. There are currently many independent efforts aimed at controlling nonpoint source contamination. They involve local health departments, county and city governments, soil conservation districts, surface water management programs, municipal sewage treatment plants, regional organizations, and neighborhood volunteer groups. Overall, trends in land use and community development--especially best management practices for animal keeping operations, proper siting and maintenance of septic systems, careful siting of sewage treatment plant outfalls, and urban stormwater control--will have the most impact on the seemingly inevitable trend of increased contamination from bacteria and viruses.

PARALYTIC SHELLFISH POISONING (PSP)

Prior to 1978, the beginning of routine testing, toxic levels of PSP ("red tide") had not been detected in Puget Sound. Since 1978, the area in which toxic plankton have been found has increased and, as of summer 1985, the only Puget Sound waters that have never been closed because of PSP are in Hood Canal and south of the Tacoma Narrows. Low levels of toxicity, not necessitating closures, have been found in Hood Canal as far south as Bangor and throughout most of the southern basin of Puget Sound. In Puget Sound, there have been no reported cases of PSP associated with the consumption of commercially harvested shellfish and only nine reported cases of PSP (in 1978) from recreationally harvested shellfish.

All species of bivalve shellfish (i.e., clams, oysters, mussels, and scallops) sampled from certain areas of Puget Sound have been found to contain PSP toxin. The rates and amounts of toxin ingested vary among these bivalves. They also vary in the time they take to detoxify once there is no longer any toxicity in the water. PSP toxins have also been found in low concentrations in other marine organisms such as limpets, snails, and Dungeness crabs but not in high enough concentrations to cause concern.

PSP is a natural phenomenon, and it is unclear whether human activities aggravate its spread. Because of the current abundance of the toxic plankton species in Puget Sound waters, it is not likely that the PSP problem it causes will disappear. There is much speculation but little evidence that the increasing incidence of PSP in Puget Sound and elsewhere in the world is related to human activities.

IV. Summary and Conclusions

THE PUGET SOUND BASIN

FORM AND PHYSICAL CHARACTERISTICS

The Puget Sound basin was formed by worldwide tectonic mechanisms and was modified by the repeated actions of ice age glaciers. The ice flowed southward from British Columbia through what is now the Strait of Georgia and over much of the Puget Sound basin. The present system developed after the most recent glaciers melted approximately 10,000 years ago.

The basin consists of several parts. The Strait of Juan de Fuca (Figure 2) and the Strait of Georgia are estuarine and separated from each other and from Puget Sound south of Admiralty Inlet by shallow ridges called sills. Puget Sound south of Admiralty Inlet is divided into four sub-basins: the Main Sub-basin which lies between Admiralty Inlet and the Tacoma Narrows; the Whidbey Sub-basin between Whidbey Island and the eastern mainland; Hood Canal; and the Southern Basin which is the most complex of the basins.

The Puget Sound basin receives from 23 to 96 inches of precipitation each year, producing an annual average flow of fresh water to the marine waters of 45,000 cubic feet per second.

ESTUARINE CIRCULATION

Puget Sound and the Straits are estuaries, bodies of seawater with large amounts of fresh water flowing into them, creating a two-layered system. Less salty water, consisting of seawater diluted by fresh water, flows toward the ocean on the surface. Deep saltier water flows toward the south or inland. In Puget Sound south of Admiralty Inlet a significant proportion of the surface water recirculates and remixes. As a result, it is estimated that fully 25 percent of wastewater discharged into the Sound halfway between Seattle and Tacoma will still be circulating in the Sound after six months.

Because sediment settles out of the surface water layer into the deep water layer, most particles of sediment are trapped in the basin. Chemical contaminants bound to particles are not washed out of the basin but are concentrated in the sediments.

Habitats

The physical nature of the basin provides a wide range of highly productive habitats. These include open water, rocky and muddy bottom habitats in deep, shallow, and intertidal depths, saltmarshes, freshwater marshes, lakes, rivers, and streams, and upland habitats ranging from broadleaf forests to alpine meadows.

These habitats have the natural capacity to support rich populations of shellfish, finfish, marine mammals, birds, and wildlife, as well as humans.

HUMAN USE AND DEVELOPEMENT

Native American residents of the basin harvested the resources of the Sound and traded for products produced elsewhere. The pattern of human use of the

History of Human Use

basin changed rapidly with the influx of non-Indian settlers beginning in the 1840s. An economy based on harvesting timber supported rapid population increases. By 1890 the regional population was 183,000 and by 1910 was more than 600,000. The economy developed rapidly, still based on harvesting natural resources including timber and fish. Agricultural production and trade also expanded. Most of the population growth was in the urban areas.

Through the first half of this century the population continued to grow. Manufacturing developed in support of fishing, shipping, and the timber industry. Trade grew in importance as did services. Improvements in transportation and changes in lifestyles led to population increases in suburban areas, lowering the overall population density and dramatically increasing the amount of developed land.

The present population of the Puget Sound basin is approximately 2.9 million. Although harvesting of resources remains an important segment of the economy, the importance of transportation, service industries, and high-technology industries has grown.

This growth in population and economy has extensively altered the uses of land in the basin. Over 500,000 acres have been developed in intensive urban development. A like amount is dedicated to agriculture. About 270,000 acres are in non-farm rural uses (largely residential and light industrial). Of the 8.6 million acres in the basin, some 80 percent remain as forest of which perhaps 50,000 acres are logged each year.

Year 2000

Between now and the year 2000, a projected population increase of 31 percent will be accompanied by a 62 percent increase in lands developed for intense urban activities and a 70 percent increase in lands developed for rural non-farm use (Tables 4 and 6). No increase is projected in agricultural land use and, along with a minor percentage decrease in land in forest use, there will be a small decrease in forest harvest activities. Employment and economic activity will shift increasingly to services, government, trade, and construction. Thus, residential, commercial, office, and retail land use will grow. Heavy industries such as pulp and paper, smelting, and others are not projected to increase significantly.

LOSS OF WETLANDS

One consequence of the conversion of the original wilderness to modern land uses is the destruction of wetland habitats. More than half of the wetland area present in the 1880s has been lost, especially the extensive mud flats and vegetated salt marshes that existed where major rivers join the Sound. The development histories of Seattle and Tacoma represent extensive conversions of wetlands to filled land in urban uses.

WATER DEPENDENT USES

The Puget Sound basin supports valuable water dependent uses including shipping, fishing, and recreation. Marine shipping may support as many as 100,000 jobs at this time.

Commercial harvests of salmon, although below the peak harvests of the 1910s, have increased lately and are stable. Large investments in management of hatchery production are necessary to maintain this harvest. Harvests of shellfish are stable although areas of the Sound previously approved for harvest are now not suitable for commercial shellfish growing. Marine food harvests in 1984 are estimated to have been worth a total of $74 million.

Although firm dollar figures are hard to come by, the value of Puget Sound as an aesthetic and recreational resource for residents and for tourists is great and unquestionable. Recreation associated with Puget Sound may account for 45,000 jobs.

CONTAMINATION OF RESOURCES

The consequences of the urbanization and industrialization of the basin include degradation of both water and sediment quality. Table 18 summarizes undesirable biological conditions, relates them to causes, and indicates their effects.

Contaminants of the Puget Sound basin include toxic chemicals, organic oxygen-demanding substances (BOD), nutrients which are damaging in excess amounts, sediment in excess amounts, biological contaminants (including pathogens--bacteria and viruses), and natural poisons such as Paralytic Shellfish Poisoning ("red tide").

SOURCES

Sources of contaminants are generally divided between point sources and nonpoint sources. Point sources, like municipal sewage treatment plants or the discharges from industries, contain a wide range of contaminants. Industrial and commercial wastewaters vary according to industrial process and may contain any of the contaminants mentioned as well as excessive acidity or alkalinity. Municipal treatment plants receive residential, commercial, and industrial wastewaters. Residential wastewater contains pathogens, sediment, oxygen-demanding materials, toxic metals, and toxic organic chemicals.

Nonpoint sources are generally tied to land use and precipitation. Agricultural runoff can contain quantities of organic (oxygen-demanding) wastes, nutrients, bacteria, sediment, and chemicals. Harvesting of timber can cause increased sediment losses and may release chemicals and pathogens. Runoff from residential areas contains pathogens, oxygen-demanding material, nutrients, and toxic chemicals. Where homes or businesses have on-site sewage treatment (septic systems), these contaminants are released when those septic systems are improperly sited or maintained. Boats are also a source of sewage. Urban development increases storm runoff because normally absorbent soil is covered by impervious surfaces. Urban stormwater runoff contains sediment, nutrients, pathogens, oxygen-demanding materials, and organic and inorganic toxic chemicals.

HISTORY

In the past 50 years, discharges of untreated sewage and industrial wastes, as well as the use of DDT, leaded gasoline, coal, and PCBs, were much greater than today. These historic discharges caused significant damage to water quality and resulted in fish kills, closure of beaches, and the creation of large

areas near cities and towns where surface waters were toxic to plants and animals. Populations of bottom-dwelling animals were also severely reduced. Installation of treatment systems for industrial wastes (particularly the pulp mills) and sewage has improved these conditions. The limited research which has been done indicates that concentrations of lead, PCBs, PAHs, and DDT in sediments were probably greater 20 years ago than they are today.

CURRENT LEVELS

Current levels of nutrients and BOD in the marine waters of the Puget Sound basin are generally not causing damage to marine life, although there are some locations where oxygen levels are periodically low.

However, toxic chemical concentrations are of concern throughout the Puget Sound basin. Sediments throughout much of the basin contain levels of metals and toxic organic chemicals that exceed pre-industrial levels. Contamination levels vary greatly from one site to the next. Hot spots of elevated sediment contamination occur in bays and lakes near urban areas and in other locations with industrial activities. Although there are no regulatory limits on levels of sediment contamination, current levels are of serious concern for several reasons. First, the general increase in contamination over natural levels is itself of concern. In addition, many sediments are toxic to organisms. Toxic chemicals in sediments are also considered a major source of contamination which has built up in the tissues of many marine organisms.

The heavily industrialized areas of Seattle (e.g., the West Waterway of the Duwamish River) and Tacoma (e.g., Hylebos Waterway) are among the most contaminated in the Puget Sound basin and contain a complex mixture of toxic substances. Eagle Harbor, west of Seattle at Winslow, is highly contaminated with hydrocarbons likely derived from creosote which was used to treat wood at a nearby factory. The harbors of Everett and Bremerton (Sinclair Inlet) have received sufficient study to identify them as areas of high contamination, but not enough to define clearly all the damaging chemicals present or their distributions. Bellingham's harbor also is significantly contaminated.

Areas that have intermediate levels of contamination (e.g., central Puget Sound between Seattle and Tacoma) are predominantly affected by the transport of contaminants by water currents from areas with major contaminant sources. Areas with low contaminant levels are generally far from major development, but even in these areas, natural transport by air and water has introduced some contaminants. Probably no area of the Sound is free from some contamination by toxic chemicals.

There is no clear evidence that toxic substances dissolved in the water are causing harm. Yet, there are many laboratory studies around the country reporting the toxicity of various chemicals when dissolved in water. These same chemicals are present in Puget Sound.

The sea surface microlayer--a thin layer of organic substances that floats on the surface of the water where eggs and larvae of many species come into contact with it--has been shown to contain toxic chemicals and, in laboratory tests, to damage marine life. The effect of microlayer contamination in Puget

Sound is not well known, although recent reports indicate that it could be severe.

Toxic chemicals that enter the waters of the Puget Sound basin are transported and transformed by a number of mechanisms. Many substances bind to particles. They are retained in the basin by estuarine circulation, and they settle and accumulate in the sediments on the Sound's bottom. Chemicals are also transformed by chemical reactions. Both organic and inorganic chemicals may be concentrated or transformed in organisms. The metabolic processes that change chemicals can produce different chemicals that are more toxic to marine life as well as breakdown products that are harmless. Marine organisms may be damaged in the process of metabolizing chemical contaminants.

Many toxic organic chemicals can be broken down to basic components. Others, like PCBs and PAHs, are extremely persistent and do not break down quickly in the environment. (PAHs can be rapidly metabolized by fish once ingested.) While the chemical form of metals can change, the amount of metal--once discharged--does not diminish over time.

Fish kills which are associated with low oxygen levels caused by natural conditions and by pollution still occur (e.g., Budd Inlet).

Marine organisms are being damaged by contamination of the Puget Sound basin. In areas with high sediment contamination levels, populations of animals living on the bottom have been altered and reduced. In addition, fish suffer pathological abnormalities including liver cancers that seem to be associated with toxic chemical contamination, especially in sediments. Birds and marine mammals accumulate levels of contamination from their food that may decrease their reproductive success.

HUMAN HEALTH ISSUES

Toxic chemicals are known to collect in the tissues of marine organisms. Even levels that may not harm the organism can pose a health risk to humans if the marine organism is a consistent element of the diet.

Elevated levels of PAHs or metals are found in fish and shellfish taken from Commencement Bay, Elliott Bay, Eagle Harbor, Everett Harbor, and Bellingham Bay.

Marine organisms, especially the clams, mussels, and oysters that obtain their food by filtering the water, can build up concentrations of pathogens that pose a risk of disease to humans. Large portions of the shallow margins of the Puget Sound basin are too contaminated to allow commercial harvesting of shellfish. The extent of such areas is increasing. Six commercial shellfish areas are no longer certified because of increasing bacterial contamination. In addition, shellfish may be contaminated above the acceptable levels for commercial sale in many recreational harvest areas.

A natural toxin, Paralytic Shellfish Poisoning, is concentrated in filter feeding bivalves such as clams, oysters, and mussels and can be toxic to humans. Although human activities have not been shown to cause the occurrence of red tide, there may be a link.

CONCLUSIONS

The marine waters of the Puget Sound basin are a naturally rich system that has been significantly altered by human activities. The basin traps and holds many types of contaminants, magnifying their potential to cause harm. Especially in Puget Sound south of Admiralty Inlet, surface water is remixed and recirculated to a great extent.

The explosion of the human population of the basin from thousands in 1800 to almost three million today has led to conversion of 20 percent of the land to human uses that are the source of many contaminants. Thirty years ago point source discharges of industrial and residential wastewater caused severe damage to marine waters and lakes of the basin. Pollution control and the banning of certain substances like DDT have resulted in lower rates of sediment contamination for some chemicals.

Although pollution control activities have resulted in significant improvements, especially in the control of oxygen-demanding materials and pathogens, serious contamination of the basin continues from both point and nonpoint sources. Runoff from both urban and rural areas, residential wastewater, and commercial and industrial discharges all contribute contaminants to the Sound.

Valuable living resources of the Sound have been reduced in abundance by overharvesting, pollution, and destruction of habitat. Marine wetlands have been seriously reduced. Intensive management efforts are required to maintain existing harvests of fish and shellfish.

In many places of the Sound, recent sediments are contaminated by harmful levels of toxic chemicals. Fish and benthic organisms are directly harmed by contamination, and the contaminants in their tissues are passed up the food web to marine mammals, birds, and humans. Pathogens (bacteria and viruses) continue to be significant contaminants in the Sound, increasingly affecting the harvest of shellfish and posing a health risk to humans.

Additional efforts to control sources of pollution will be required to prevent increased contamination of the Sound in the future, especially since the projected 30 percent increase in population by the year 2000 will be accompanied by increased rates of land development. Wastewater flows associated with residential and commercial development and urban stormwater will increase significantly, while runoff from agricultural lands and forest practices may not.

The most acute chemical contamination problem in the Puget Sound basin is the concentration of toxic chemicals in sediments in specific locations. Sources of toxic chemicals to these hot spots include urban storm drains, combined sewer overflows, and illegal industrial discharges, all of which are untreated and discharged in shallow water. Industrial and residential wastewaters that are inadequately treated for toxic chemicals also contribute to contamination of sediments, both in hot spots and throughout the Sound.

Reporting of chemical contamination of the Sound is always incomplete. There are thousands of chemical compounds in use today but only about a hundred compounds in the environment are routinely monitored and studied. New

chemicals are introduced to the marketplace regularly. In some cases, levels of a known toxic compound may decrease because the chemical has been replaced by a different compound, but the replacement may not be on any list for routine analysis.

The complexity of the Puget Sound system results in complexity in the transport, fate, and effects of contaminants. Changes in population and land use will naturally change the types, distribution, and amounts of contaminants discharged to the waters of the basin. Science is unable, and will always be unable, to detect environmental damage to Puget Sound as soon as it occurs, wherever it occurs. Therefore, a management approach that requires demonstrated harm in some part of the system before reductions in discharges of contaminants are required will not protect the Sound. By the time a sediment hot spot is identified, or a shellfish bed must be closed, or a pollution-caused decline in a valuable organism is detected, Puget Sound will have already suffered damage.

GLOSSARY

ACCUMULATION RATE
Rate at which organic and inorganic sediment collects on the bottom of a body of water.

AEROBIC
Living, active, or occurring only in the presence of oxygen. For instance, soil microorganisms which degrade sewage effluent from septic systems need oxygen in order to function.

ALGAE
Aquatic, nonflowering plants which lack roots and live on inorganic nutrients such as nitrogen and phosphorous and produce organic matter by photosynthesis. Common algae include those that are single celled such as dinoflagellates, diatoms, and also seaweeds and kelp. An algal bloom can occur when excessive nutrients and certain water conditions enable the organisms to reproduce rapidly.

AMPHIPODS
A large group of crustaceans composed of sand fleas and other related forms of animals. Many feed on algae and look like small shrimp.

ANADROMOUS FISH
Species, such as salmon, which spend most of their lives in the sea but travel up freshwater rivers and streams to breed.

ANAEROBIC
Living or active in the absence of oxygen. There are some bacteria which function only in the absence of oxygen.

ANOXIC
Having little or no oxygen. Anoxic sediments tend to become black and smelly.

ANTHROPOGENIC
Caused or created by humans. For instance, many pesticides are anthropogenic.

AROMATIC
A chemical substance characterized by the presence of at least one benzene ring. These substances are often persistent in the environment due to the stability of the benzene ring.

BAITFISH
Group of pelagic marine fish including herring, smelt, and anchovy.

BASIC INDUSTRIES
Industries whose output is traded to other regions. The output from non-basic industry is consumed locally and is not traded to other regions.

BENTHIC ORGANISM
Organisms which live in or on the bottom of a body of water.

BEST MANAGEMENT PRACTICE (BMP)
Refers to methods for preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals. The term originated with the rules and regulations developed pursuant to Section 208 of the Federal Clean Water Act (40 CFR, Part 130).

BIOACCUMULATION
The process by which a contaminant accumulates in the tissues of an individual organism. For example, certain chemicals in food eaten by a fish tend to accumulate in its liver and other tissues.

BIOASSAY
A test procedure that measures the response of living plants, animals, or tissues to a sample. For example, amphipods have been exposed to the sediments of Puget Sound and their responses have been used to determine areas in the Sound where the sediment may be harmful to life.

BIOCHEMICAL OXYGEN DEMAND (BOD)
The quantity of materials present in a sample that need oxygen to decay, as measured by a specific test. A major objective of wastewater treatment is to reduce its biochemical oxygen demand so that the oxygen content of the water body will not be significantly reduced. Although BOD is not a specific compound, it is defined as a conventional pollutant under the Federal Clean Water Act.

BIODEGRADATION
The conversion of organic compounds into simpler compounds through biochemical activity. Toxic compounds can sometimes be converted into nontoxic compounds through biodegradation. Unfortunately, in some cases, complex compounds are first converted into intermediate substances that can be more toxic than the original substance.

BIOLOGICAL TREATMENT
A wastewater treatment process that utilizes heavy growth of microorganisms for the purpose of oxidizing, absorbing, and adsorbing wastewater impurities, both organic and inorganic. Secondary treatment plants usually provide biological treatment.

BIOMAGNIFICATION
The process by which concentrations of contaminants increase (magnify) as they pass up the food chain so that each animal in the chain has higher tissue concentrations than did its food. For example, concentrations of certain contaminants can increase as they are passed from herring to salmon to seals.

BIOMASS
The total weight of a group of organisms.

BIOTA
The animals and plants that live in a particular location or region.

BOTTOMFISH
Fish that live on or near the bottom of the water, for example, English sole.

CARCINOGENIC
Capable of causing cancer. A carcinogen is a chemical compound capable of causing cancer.

CARNIVORE
Animals that eat only other animals.

CERTIFIED
Areas approved by the Department of Social and Health Services for commercial shellfish harvesting.

CHLOROPHYLL
Principal green plant pigment which allows plants to grow using only sunlight, water, and some nutrients. Often used as a measure of the biomass of plants.

CLEANUP ACTIVITIES

Actions taken by a public agency or a private party to correct an environmental problem. Activities can include either the prevention of pollution by the treatment or control of contaminants (for example, treatment of wastewater before discharge) or the removal from the environment of contaminants introduced by past practices (for example, digging up and incinerating soil contaminated with dioxin).

COE

U.S. Army Corps of Engineers

COLIFORM BACTERIA

A type of bacteria which includes many species. Fecal coliform bacteria are those coliform bacteria which are found in the intestinal tracts of mammals. The presence of high numbers of fecal coliform bacteria in a water body can indicate the release of untreated wastewater, and/or the presence of animals, and may indicate the presence of pathogens.

COMBINED SEWER OVERFLOW (CSO)

A pipe that discharges untreated wastewater during storms from a sewer system that carries both sanitary wastewater and stormwater. The overflow occurs because the system does not have the capacity to transport and treat the increased flow caused by stormwater runoff.

COMMERCIAL CATCH

Harvest of fish or shellfish with the intent to sell catch. Commercial catch has to meet certain health restrictions.

COMMUNITY

A group of interacting organisms living within a localized region, defined by a particular habitat.

CONTAMINANT

A substance that is not naturally present in the environment or is present in unnatural concentrations or amounts and which can, in sufficient concentration, adversely alter an environment. Contaminant sinks are the areas in the environment where contaminants accumulate over time, for example, sediments in urban embayments.

CONVENTIONAL CONTAMINANT

Conventional contaminants as specified under the Clean Water Act are total suspended solids, coliform bacteria, biochemical oxygen demand, pH, and oil and grease. pH is a measure of the acidity or alkalinity of the water. Today a large number of toxic contaminants are of concern in addition to the conventional contaminants.

CORE SAMPLES

Samples taken by inserting a hollow tube into the substrate. The tube fills with the substrate, and the result is a tube-shaped sample with the older material on the bottom and the younger material on the top.

CRUSTACEANS

A large class of arthropods which have a stiff or hard exoskeletons and are often segmented. Shrimps, crabs, and barnacles are all crustaceans.

CUMULATIVE EFFECTS

The term refers to the combined environmental impacts that accrue over time and space from a series of similar or related individual actions, contaminants, or projects. Although each action may seem to have an negligible impact, the combined effect can be severe.

CWA
The federal Clean Water Act, previously known as the Federal Water Pollution Control Act.

DEPOSITION
The accumulation of sediments on the bottom by either physical processes or chemical reactions.

DETENTION
The process of collecting and holding back stormwater for later release to receiving waters.

DETRITUS
Non-living particles, suspended in the water column or on the bottom. Many animals, particularly filter-feeding worms, exist mainly by eating detritus.

DISINFECTION
The partial destruction of infectious agents such as bacteria or viruses. Most wastewater treatment plants use chlorine for disinfection.

DISPOSAL
A method by which unwanted materials are eliminated. Unfortunately, unless contaminants are converted to less harmful substances or removed from the material before disposal, they may be released into the environment. In these cases the waste has only been relocated.

DISSOLVED OXYGEN
Oxygen which is present (dissolved) in water and therefore available for fish and other aquatic animals to use. If the amount of dissolved oxygen in the water is too low, marine animals suffer from suffocating. Wastewaters often contain oxygen demanding substances which can consume dissolved oxygen if discharged into the environment.

DOMESTIC WASTEWATER
The wastewater that flows from sinks, toilets, showers, and other facilities that are routinely used by people.

DNR
Washington State Department of Natural Resources

DREDGING
Any physical digging into the bottom of a water body. Dredging can be done with mechanical or hydraulic machines and changes the shape and form of the bottom. Dredging is routinely done in many parts of Puget Sound in order to maintain navigational channels which would otherwise fill with sediment and block the passage of ships.

DSHS
The Washington Department of Social and Health Services, which is responsible for implementing public health legislation.

ECOLOGY (DOE)
The Washington Department of Ecology, which is responsible for implementing many environmental protection laws including the state Clean Water Act and the Shoreline Management Act. Note that the abbreviation DOE is confusing because the federal Department of Energy uses the same term. Ecology is the preferred term for referring to the Department of Ecology.

ECONOMIC BASE
The portion of the output of an economy that is traded to people and industries in other areas.

ECOSYSTEM
A community of living things interacting with one another and with their physical environment, such as a rain forest, pond, or estuary. An ecosystem, such as Puget Sound, can be thought of as a single complex system. Damage to any part may affect the whole. A system such as Puget Sound can also be thought of as the sum of many interconnected ecosystems such as the rivers, wetlands, and bays. Ecosystem is thus a concept applied to various scales of living communities and signifying the interrelationships that must be considered.

EFFLUENT
The liquid flowing out of a facility or household into a water body or sewer system. For example, the treated liquid discharged by a wastewater treatment plant is the plant's effluent.

EPA
The U.S. Environmental Protection Agency, which administers many federal environmental laws. Region 10, which includes Puget Sound, is headquartered in Seattle.

EROSION
Detachment of soil or rock fragments by water, wind, ice, and gravity.

ESCAPEMENT
The proportion of fish stocks protected from harvest to allow natural propagation.

ESTUARY
A confined coastal water body where fresh and salt waters meet and tides are experienced.

EUTROPHIC
Describes a water body that has built up excess nutrients so that excess plant growth occurs. As a result, large amounts of plant material decay and consume dissolved oxygen. Thus, less dissolved oxygen is available to aquatic life. Eutrophication is the process by which this occurs.

EVAPOTRANSPIRATION
A collective term for the processes of evaporation and plant transpiration by which water is returned to the atmosphere from the land.

EX-VESSEL VALUE
Price paid to fishermen for fishing products off-loaded from a fishing vessel to a fish processor.

FAUNA
A collective term for the animal life in an ecosystem.

FJORD
A long, narrow, steep-sided marine inlet, carved by a glacier, usually with a sill at the mouth.

FLOCCULATION
Aggregation of small suspended particles into a loose mass caused by ionic changes due to contact with seawater. Many contaminants carried into Puget Sound by fresh water change form through this process when the freshwater reaches the Sound.

FLORA
A collective term for the plant life in an ecosystem.

FOOD WEB
A community of organisms which are connected by dependence upon one another for food.

FOREST PRACTICE
Any activity conducted on or directly pertaining to forest land and relating to growing, harvesting, or processing timber. These activities include but are not limited to: road and trail construction; final and intermediate harvesting; precommercial thinning; reforestation; fertilization; prevention and suppression of disease and insects; salvage of trees; and brush control.

GLACIER
A mass of ice and snow that persists throughout the year and flows downhill due to gravity.

GRAM
A metric unit of measure equal to 0.035 ounces.

GROUNDWATER
Underground water supplies, also called aquifers. Aquifers are created by rain which soaks into the ground and flows down until it is collected at a point where the ground is not permeable. Groundwater then usually flows laterally toward a river or lake or the ocean. Wells tap the groundwater for our use.

HABITAT
The specific area or environment in which a particular type of plant or animal lives. An organism's habitat must provide all of the basic requirements for life and should be free of harmful contaminants. Puget Sound habitats include beaches, marshes, rocky shores, the bottom sediments, mudflats, and the water itself.

HAZARDOUS WASTE
Any solid, liquid, or gaseous substance which, because of its source or measurable characteristics, is classified under state or federal law as hazardous and subject to special handling, shipping, storage, and disposal requirements. Washington state law identifies two categories, dangerous and extremely hazardous. The latter category is more hazardous and requires greater precautions.

HERBICIDE
A substance used to destroy or inhibit growth of vegetation.

HERBIVORE
An animal that eats only plants.

HYDROCARBON
A class of organic chemicals composed of hydrogen and carbon. Environmentally important hydrocarbons include PAHs.

HYDROLOGICAL CYCLE
The continual exchange of moisture between the earth and the atmosphere consisting of evaporation, condensation, rain, snow, absorption into the soil, and stream runoff.

INFILL
The concept of encouraging development within developed areas rather than in outlying areas. This is considered to be a more efficient development pattern than outward sprawl as it utilizes existing utilities and services before their extension to new areas.

INFRASTRUCTURE
Streets, utilities, parks, and other elements that support residential development and other socioeconomic activities.

IMPERVIOUS
A surface which cannot be easily penetrated. For instance, rain does not readily penetrate paved surfaces.

INDIGENOUS
A life form that is native to a particular region or environment.

INDUSTRIAL USER
A commercial or industrial facility which discharges anything other than domestic waste to a sewage treatment plant. Industrial users may be subject to pretreatment requirements.

INFAUNA
The benthic invertebrates that live beneath the sediment.

INFLOW AND INFILTRATION
Excess water that enters a sewer system. Since a sewer system can only handle a certain amount of wastewater at one time, excess flow can trigger overflows of raw wastewater. Inflow refers to water that unnecessarily flows into the system, for example, from household roof drains. Infiltration is water that seeps into the system through cracks and gaps in the pipes. Typically, inflow and infiltration are clean water not needing treatment.

INSECTICIDE
A substance, usually chemical, that is used to destroy insects.

INTERTIDAL AREA
The area between high and low tide levels.

IONS
An atom or group of atoms carrying a positive or negative charge as a result of having gained or lost one or more electrons.

ISOTOPE
A form of an element that occurs as two or more types of atoms whose nuclei have the same number of protons but different numbers of neutrons. Isotopes of an element have the same nuclear charge but different weights.

KILOGRAM
Metric unit of weight equal to one thousand grams or 2.2 pounds.

KILOMETER
One thousand meters; 0.62 miles (square kilometer equals 0.4 square miles or 2.47 acres).

LACUSTRINE
Wetland habitat existing in and around lakes.

LAND USE
The way land is developed and used in terms of the types of activities allowed (agriculture, residences, industries, etc.) and the size of buildings and structures permitted. Certain types of pollution problems are often associated with particular land use practices, such as sedimentation from construction activities.

LARVA
A juvenile stage of an organism with a body form which differs from the adult stage.

LEACHATE
A soluble material, such as organic and mineral salts, which is washed out of a layer of soil or debris.

LESION
An abnormal structural change in the body of an organism due to injury or disease, for example, liver tumors in fish.

LIPID
Fat or oil molecule.

LITER
A metric unit of volume equal to one thousand cubic centimeters or 1.06 quarts.

LOAD
The total amount of material or substances present in a given system.

MEAN ANNUAL FLOW
The average amount of water that flows past a given point in one year.

MEDIUM, MEDIA
In pollution control programs, media are the components of the environment that may be contaminated with a substance. Thus, lead can be discharged to the air, to the water, or on the land. A program that handles lead contamination in all media is a cross-media program. A disposal practice that allow contaminants to go from water to air allows cross-media transfers.

METABOLISM
All chemical processes occurring within an organism; includes both synthesis and breakdown of organic materials, including the digestion of food.

METER
A metric unit of length equal to 3.28 feet or 1.09 yards (a square meter equals 10.7 square feet; a cubic meter equals 35.3 cubic feet or 1.3 cubic yards).

METALS
Elements, such as mercury, lead, nickel, zinc, and cadmium, that are of environmental concern because they do not degrade over time. Although many are necessary nutrients, they are sometimes magnified in the food chain, and they can be toxic to life in high enough concentrations.

METRIC TON
One thousand kilograms; 2200 pounds; 1.1 English tons.

METRO
Municipality of Metropolitan Seattle

MICROGRAM
One millionth of a gram.

MICROLAYER
An extremely thin layer of organic substances that is part of the top layer of water. It is of concern because contaminants such as oil, grease, toxicants, and pathogens may be present at much higher concentrations in the microlayer than they are in the water column and may therefore pose a danger to fish eggs and other organisms that live at the surface.

MICROORGANISMS
Minute organisms, such as bacteria, which are barely visible to the unaided eye.

MILLIGRAM
One thousandth of a gram.

MOLLUSCS
Invertebrate animals which often have a hard shell such as clams and snails.

MONITOR
To systematically and repeatedly measure something in order to track changes. For example, dissolved oxygen in a bay might be monitored over a period of several years in order to identify any trends in its concentration.

MUNICIPAL DISCHARGE
Effluent from a sewage treatment plant that is usually publicly-owned.

NEOPLASM
A tumorous cell growth.

NEPHLOID LAYER
A cloudy or turbid water layer in which light is scattered and absorbed by suspended particles. In the main basin of Puget Sound, the cloudiness of water increases near the bottom because fine particles are repeatedly suspended from the bottom.

NOAA
National Oceanic and Atmospheric Administration.

NONPOINT SOURCE
A non-specific source of pollutants, often from a large area.

NPDES
National Pollutant Discharge Elimination System. A part of the Federal Clean Water Act, which requires point source dischargers to obtain permits. These permits are referred to as NPDES permits and are administered by the Washington State Department of Ecology.

NUTRIENTS
Essential chemicals needed by plants or animals for growth. Excessive amounts of nutrients can lead to degradation of water quality and the growth of excessive numbers of algae. Some nutrients can be toxic at high concentrations.

OMNIVORE
An animal that eats both plants and animals.

ON-SITE SEPTIC SYSTEM
A sewage treatment system where waste is treated on the owner's property, generally by means of bacterial breakdown in an underground septic tank and removal of organics by percolation of wastewater through a drainage field.

ORGANIC
Pertaining to or derived from organisms; a chemical containing a carbon complex.

PAH

Polycyclic (polynuclear) aromatic hydrocarbon. A class of complex organic compounds, some of which are persistent and cancer-causing. These compounds are formed from the combustion of organic material and are ubiquitous in the environment. PAHs are found in fossil fuels such as coal and oil and are formed by incomplete combustion of organic fuels like gasoline, wood, and oil. They are commonly formed by forest fires, wood stoves, and internal combustion engines. They often reach the aquatic environment through atmospheric fallout and highway runoff.

PALUSTRINE

Upland habitats of a marshy or wetland nature.

PARALYTIC SHELLFISH POISONING (PSP)

An illness, sometimes fatal to humans, caused by a toxin produced by a type of plankton called Gonyaulax. During certain times of the year and at certain locations, these organisms proliferate in blooms (sometimes called "red tides") and can be concentrated in clams, mussels, and other bivalves. Consumption of the shellfish can then cause an acute illness.

PARAMETER

A characteristic substance or factor that is measured in order to describe a system. The Department of Ecology routinely measures numerous parameters such as pH, in order to gain an understanding of water quality in Puget Sound.

PATHOGEN

A disease-causing agent, especially microorganisms such as viruses, bacteria, or fungi which can be present in municipal, industrial, and nonpoint source discharges to the Sound.

PCBs

Polychlorinated biphenyls including about 70 different but closely related man-made compounds made up of carbon, hydrogen, and chlorine. They persist in the environment and can biomagnify in food chains because they are not water-soluble. PCBs are suspected to cause cancer in humans. PCBs are an example of an organic toxicant.

PELAGIC

Contained within a body of water, not on the bottom.

PERCOLATION TEST

A test which measures the rate of movement of water into the soil, and helps determine the ability of the soil to absorb waste.

PERSISTENT

Compounds that are not readily degraded by natural physical, chemical, or biological processes.

PESTICIDE

A general term used to describe any substance--usually chemical--used to destroy or control organisms including herbicides, insecticides, algicides, fungicides, and others. Many of these substances are manufactured and are not naturally found in the environment. Others, such as pyrethrum, are natural toxins which are extracted from plants and animals.

pH

A measure of the alkalinity or acidity of a substance determined by the concentration of hydrogen ions in the substance. A pH of 7.0 indicates neutral water. A pH of 2 is extremely acidic, while a pH of 13 is extremely basic or alkaline.

PLANKTON

Small plants and animals that are suspended in the water and either drift with the currents or swim weakly. Phytoplankton are plants that use light to make food. Zooplankton are animals that eat phytoplankton and each other.

POINT SOURCE

A source of pollutants from a specific pipe. Generally, any pipe which is regulated by NPDES is considered to be a point source.

POLLUTANT

A contaminant that adversely alters the physical, chemical, or biological properties of the environment. The term includes pathogens, toxic metals, carcinogens, oxygen-demanding materials, and all other harmful substances. Particularly with reference to nonpoint sources, the term is sometimes used to apply to contaminants arising in low concentrations from many activities which collectively degrade water quality.

PPB

Parts per billion; one part in one billion by weight, or one milligram per metric ton.

PPM

Parts per million; one part in one million, or one gram per metric ton.

PRE-NEOPLASM

A cluster of altered cells that may be a precursor to a malignant tumor or neoplasm.

PRETREATMENT

The treatment of wastes to remove contaminants prior to discharge into municipal sewage systems.

PRIMARY ECONOMIC PRODUCTS

Resource-based products produced in an area such as agricultural, mining, fishing and forestry products.

PRIMARY TREATMENT

A wastewater treatment method that uses settling, skimming, and chlorination to remove solids, floating materials, and pathogens from wastewater. Primary treatment removes about 35 percent of BOD and less than half of the metals and toxic organic substances.

PRIORITY POLLUTANTS

Substances listed by EPA under the Clean Water Act as toxic and having priority for regulatory controls. The list includes toxic metals, inorganic contaminants such as cyanide and arsenic, and a broad range of both natural and artificial organic compounds. The list of priority pollutants probably includes substances which are not of concern in Puget Sound and does not include all known harmful compounds.

PSWQA

Puget Sound Water Quality Authority.

PUBLIC DOMAIN

Land owned or controlled by the state or federal government.

RESIDENCE TIME

Average time spent by a water parcel in a basin before being flushed out to sea.

RESPIRATION
The sum total of metabolic processes associated with conversion of stored chemical energy into physical energy to be used by the organism.

RIPARIAN
Pertaining to the banks of streams, lakes, or tidewater.

SALINITY
A measure of the quantity of dissolved salts in seawater.

SALMONID
A fish of the family Salmonidae. Fish in this family include salmon and trout. Many Puget Sound salmonids are anadromous.

SANITARY WASTEWATER
Wastewater which includes sewage and may contain pathogens. Sanitary wastewater is not sanitary.

SECONDARY TREATMENT
A wastewater treatment method that usually involves the addition of biological treatment to the settling, skimming, and disinfection provided by primary treatment. Secondary treatment may remove up to 90 percent of BOD and significantly more metals and toxic organics than primary treatment.

SECTOR
A set of industries producing a similar set of products.

SEDIMENT
Material suspended in or settling to the bottom of a liquid, such as the sand and mud that make up much of the shorelines and bottom of Puget Sound. Sediment input to Puget Sound comes from natural sources such as erosion of soils and weathering of rock or anthropogenic sources such as forest or agricultural practices or construction activities. Certain contaminants tend to collect on and adhere to sediment particles. The sediments of several areas around Puget Sound contain elevated levels of toxic contaminants.

SHELLFISH
An aquatic animal such as a mollusc or crustacean having a shell or shell-like exoskeleton.

SHELLFISH CONTAMINATION
The contamination of certain bivalves (clams, mussels, oysters) which filter water to feed and tend to collect or concentrate waterborne contaminants in their tissues.

SHORELINE DEVELOPMENT
As regulated by the Shoreline Management Act, the construction over water or within a shoreline zone (generally 200 feet landward of the water) of structures such as buildings, piers, bulkheads, and breakwaters, including environmental alterations such as dredging and filling or any project which interferes with public navigational rights on the surface waters.

SILL
Shallow submerged pile of debris left across a basin by a retreating glacier; called a moraine on land.

SILTATION
The process by which a river, lake, or other water body becomes clogged with sediment. Silt can clog gravel beds and prevent successful salmon spawning.

SLUDGE
Precipitated or settled solid matter produced by sewage treatment processes.

SMOLT
A salmon or sea trout that is making its first descent to the sea from the fresh water where it was born.

SOIL PERMEABILITY
The ease with which gases, liquids, or plant roots penetrate or pass through a layer of soil.

SORPTION
The process whereby dissolved substances physically or chemically bind to the surface of particles.

SPORT CATCH
Harvest of fish or shellfish for personal consumption or use.

STOCK or POPULATION
A discrete group of fish usually identified by species and geographic location.

STORMWATER
Water that is generated by rainfall and is often routed into drain systems in order to prevent flooding.

STORM DRAIN
A system of gutters, pipes, or ditches used to carry stormwater from surrounding lands to streams, lakes, or Puget Sound. Often carries a variety of substances such as oil and antifreeze which enter the system through runoff, deliberate dumping, or spills. This term also refers to the end of the pipe where the stormwater is discharged.

STRATIFIED ESTUARY
An estuary with a freshwater layer floating on top of a saltwater layer flowing in opposite directions.

SUBTIDAL
Area below the intertidal zone, usually delineated by the mean lower low tide level.

SUPERFUND
EPA and Ecology program to clean up hazardous waste sites or other areas of toxic contamination.

SUSPENDED SOLIDS
Organic or inorganic particles that are suspended in and carried by the water. The term includes sand, mud, and clay particles as well as solids in wastewater.

SYNTHETIC ORGANIC CHEMICALS
Chemicals which do not occur naturally but as products of human activity. These chemicals are difficult to degrade and tend to accumulate in the environment.

TECTONICS
The movements and deformation of the earth's crust on a large scale. Tectonic plates are the large pieces of crust which float on a semi-liquid layer. These plates may collide and be pushed over and under one another to form geologic features such as mountain ranges and ocean trenches.

TERATOGENIC
Causing birth defects.

TOTAL CATCH

The total harvest of fish in an area such as Puget Sound by commercial, sport, and Indian fisheries, generally expressed as number of individuals or groups of species.

TOXIC

Poisonous, carcinogenic, or otherwise directly harmful to life.

TOXIC SUBSTANCES AND TOXICANTS

Chemical substances, such as pesticides, plastics, detergents, chlorine, and industrial wastes that are poisonous, carcinogenic, or otherwise directly harmful to life.

TREATMENT

Chemical, biological, or mechanical procedures applied to an industrial or municipal discharge or to other sources of contamination to remove, reduce, or neutralize contaminants.

TURBIDITY

A measure of the amount of material suspended in the water. Increasing the turbidity of the water decreases the amount of light that penetrates the water column. High levels of turbidity are harmful to aquatic life.

VIRUS

An ultramicroscopic parasite which cause diseases such as hepatitis, polio and cancerous growths.

VOLATILE

Easily vaporized at a relatively low temperature.

VOLATILIZATION

The evaporation of substances, especially those with low boiling points. For example, cleaning fluids discharged into the sewer system may evaporate into the atmosphere in the pipes and in the sewage treatment plant.

WASTEWATER TREATMENT SLUDGE

Semi-solid matter resulting from the treatment of wastewater. Some of the contaminants that were in the wastewater remain in the sludge after treatment. The treated wastewater can be discharged to the Sound, but the sludge must be disposed of elsewhere. Sludge is usually at least partially dried before disposal and may be added to soil to increase plant growth.

WATERS OF PUGET SOUND

As defined in RCW 90.70.005, all salt waters of the state of Washington inside the international boundary line between Washington and British Columbia, and lying east of 123o 24' west longitude (east of Port Angeles).

WATERSHED

All land from which precipitation collects and drains to a common point, also known as a drainage basin.

WATER DEPENDENT INDUSTRY

Activities which find a waterfront location either necessary for business or a key locational advantage. Examples include aquaculture, shipping, marine manufacturing, and restaurants.

WATER TABLE

The upper surface of groundwater, or the level below which the soil is saturated with water.

WEATHERING

Processes that decay and break up bedrock by a combination of physical fracturing and chemical decomposition.

WETLANDS

Habitats where the influence of surface or groundwater has resulted in development of plant or animal communities adapted to aquatic or intermittently wet conditions. Wetlands include tidal flats, shallow subtidal areas, swamps, marshes, wet meadows, bogs, and similar areas.

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