Water-Quality Assessment of the Puget Sound Basin, Washington--Environmental Setting and Its Implications for Water Quality and Aquatic Biota

By Ward W. Staubitz, Gilbert C. Bortleson, Sheila D. Semans, Anthony J. Tesoriero, and Robert W. Black

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FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for a specific contamination problem; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

•Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.

•Describe how water quality is changing over time.

•Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 60 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 60 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Chief Hydrologist

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4 2.54	millimeter centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Mass	
pound (lb)	0.4536	kilogram
	Area	
acre	0.4047	hectare
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785 3,785	liter milliliter
cubic mile (mi^3)	4.168	cubic kilometer
cubic yard (yd^3)	0.765	cubic meter
cubic feet (ft^3)	0.02832	cubic meter
	Flow	
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/day)	0.04381	cubic meter per second
cubic feet per second (ft^3/sec)	0.02832	cubic meter per second
Hydraulic Conductivity		
foot per day (ft/day)	0.3048	meter per day

	Transmissivity	
square foot per day (ft^2/day)	0.09290	square meter per day
	0.01075	square centimeter per second

Physical and Chemical Water-Quality Units

Temperature: Water and air temperature are given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by use of the following equation: °F = 1.8 (°C) + 32

Specific electrical conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius.

Milligrams per liter (mg/L) or micrograms per liter (µg/L): Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

The Puget Sound Basin in Washington is one of 60 study units selected for water-quality assessment as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) program. The Puget Sound Basin study unit encompasses the fresh surface and ground waters in the 13,700 square-mile area that drains to Puget Sound but does not include the marine waters of Puget Sound. Defining the environmental setting of the study unit is the first step in designing and conducting a multi-disciplinary regional water-quality assessment. This report describes the natural and human factors that affect water quality in the basin and includes an overview of the physiography, geology, soils, surface- and ground-water hydrology, land use, instream habitat, and the aquatic ecosystem. The report also provides an overview of existing water-quality conditions and summarizes the results of selected water-quality studies of the basin. This information indicates that the quality of fresh water in the Puget Sound Basin is generally good, although in agricultural and urban areas, surface water is degraded in places by fecal-coliform bacteria, and nitrate at undesirable levels is found in some aquifers. Toxic materials from terrestrial sources also discharge to Puget Sound and accumulate in bottom sediments, and the physical hydrology, water temperature, and biologic integrity of many streams have been degraded to varying degrees by logging in the upper forested watersheds and by agricultural and urban development in the lower watersheds.

INTRODUCTION

The Puget Sound Basin is one of 60 study units to be investigated under the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) program. The long-term goals of the NAWQA program are to describe the status and trends in the quality of a large representative part of the Nation's surface- and ground-water resources and to provide a sound, scientific understanding of the major natural and human factors that affect the quality of these resources (Leahy and others, 1990). The NAWQA program is designed to address water-quality issues at multiple scales, and the study units constitute the principal building blocks of the NAWQA program. The results of the study unit investigation will provide information that is useful for understanding and managing the water resources of the study unit, and the results will be aggregated with equivalent information from other study units to assess regional and national scale water-quality issues.

The Puget Sound Basin study unit encompasses the 13,700-mi^2 (square-mile) area that drains to Puget Sound and its adjacent waters, including lands that drain to the Strait of Georgia below the Canadian border and to the eastern part of the Strait of Juan de Fuca. The study unit includes the islands, but not the marine waters, of Puget Sound. It encompasses all or part of 13 counties in western Washington, as well as the headwaters of the Skagit River and part of the Nooksack River Basin in British Columbia, Canada (fig. 1). About 3.7 million people, or 70 percent of the population of Washington State, live in the Puget Sound Basin.

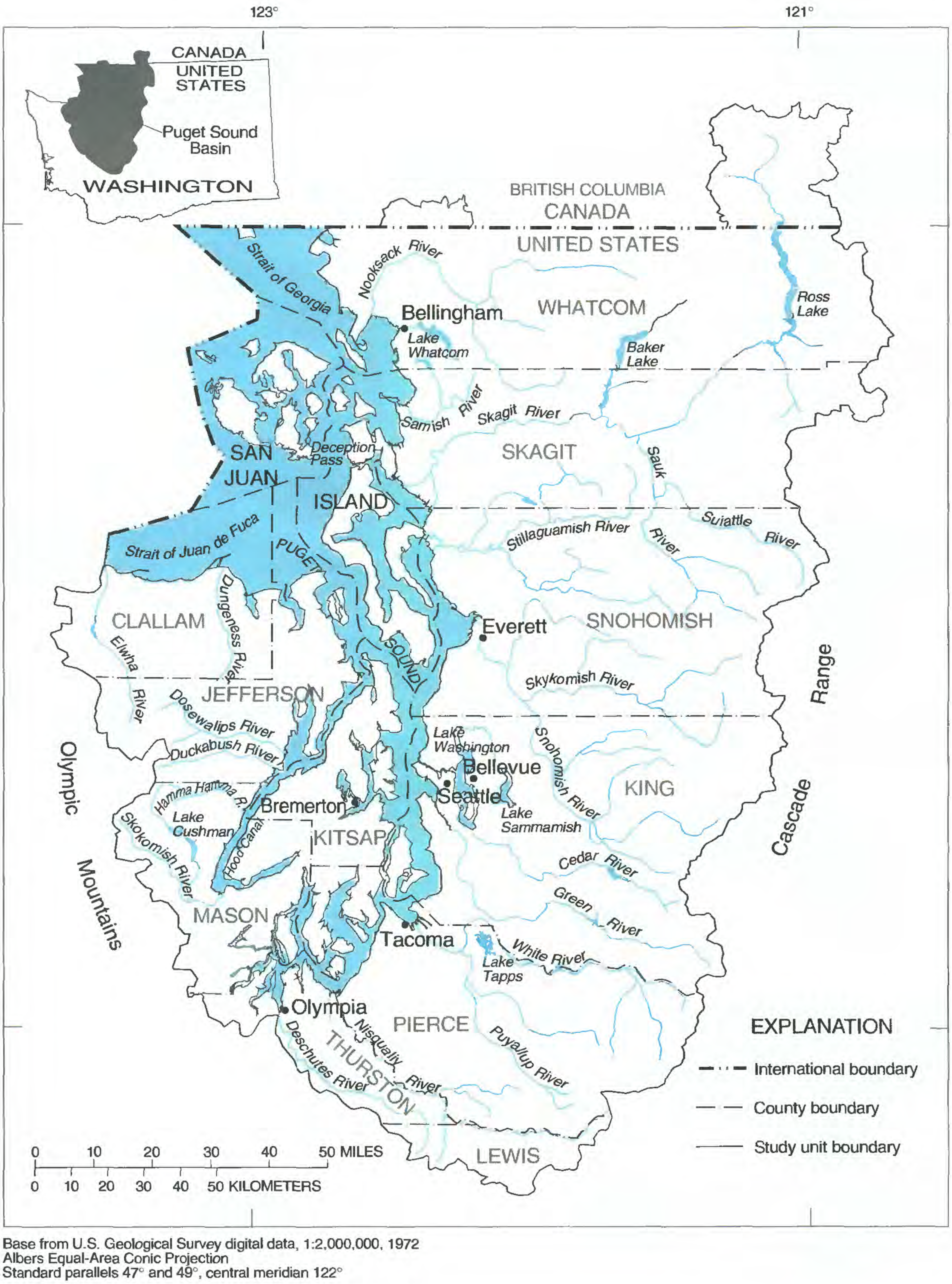


Figure 1. Puget Sound Basin NAWQA study unit.

Purpose and Scope

This report describes the natural and human factors that are believed to control or have a large-scale or regional influence on the current (1996) water quality of the Puget Sound Basin. This information defines the environmental setting of the study unit and is collected and evaluated as the first step in designing and conducting a multidisciplinary water-quality assessment of the basin. The report will be useful to design the NAWQA data collection program for the Puget Sound Basin study unit, and base-line information contained in the report will be incorporated into future data analyses and referenced in future reports addressing specific water-quality issues of the study unit and in reports integrating data from the Puget Sound Basin into national or regional water-quality assessments.

The report describes the natural factors of physiography, bedrock geology, soils, climate, and hydrology that largely determine the natural background quality of water and the cultural factors of population, land and water use, and waste-management practices that largely define the human influence on water quality. The report further summarizes the results of selected water-quality studies and provides an overview of existing water-quality conditions in the Puget Sound Basin.

Previous Studies

The description of the environmental setting is based on a review of currently available information, reports, and data from Federal, State, local, and Canadian agencies. Much of this information was derived from hydrologic reports by the Pacific Northwest River Basins Commission (1970a,b,c), the Puget Sound Water Quality Authority (1988 and 1992), and the U.S. Geological Survey's Puget Sound Lowland Regional Aquifer Study (Vaccaro and others, in press).

ENVIRONMENTAL SETTING OF THE PUGET SOUND BASIN

The Puget Sound Basin contains a varied landscape that ranges from broad, flat tidelands and alluvial valleys, to rolling hills of glacial drift, and steep mountains. The mild-rainy marine climate, densely forested slopes, volcanic peaks, migrating salmon, and islands and shores of Puget Sound are all defining features of the basin, as are the cities and farms and expanses of clear-cut forest. The rivers and streams in the basin drain from many separate watersheds directly into Puget Sound. Although each of these watersheds is unique, and the quality of water in the streams is influenced to varying degrees by a range of environmental factors, the watersheds share many common characteristics and the range of water-quality conditions are similar and comparable. The natural and human factors that have a large-scale or regional influence on water quality in the Puget Sound Basin define the basin's environmental setting, and these factors are described below.

Physiography

The Puget Sound Basin encompasses parts of three physiographic provinces and includes the Olympic Mountains in the west and the Cascade Range in the east, which compose about one-half of the study unit land area, and the Puget Sound Lowland, in the middle, which composes the rest (fig. 2). Both the Cascade Range and the Olympic Mountains are rugged, largely uninhabited, mountainous terrain with bare rock peaks, steep forested slopes, and deep valleys and canyons. The crest of the Cascade Range averages about 7,500 feet in altitude, with mountain peaks reaching an altitude of as much as 9,000 feet in the north and 7,000 feet in the south. Three stratovolcanos, Mount Baker (10,788 feet), Glacier Peak (10,541 feet), and Mount Rainier (14,410 feet) rise above the Cascade Mountain ridges and support numerous glaciers. Glaciers also are found on numerous other peaks in the northern Cascade Range.

The north-south trending Cascade Range is bisected by east-west trending alluvial valleys, with mountain ridges forming the drainage divides in between. The alluvial valleys are narrow and steep at the higher altitudes and broad and flat downstream as they traverse the lowlands. Streams from these valleys join to form eight major rivers that drain the western slope of the Cascade Range and discharge to Puget Sound.

The crest of the Olympic Mountains averages about 3,000 feet, and the mountain peaks range in altitude up to 8,000 feet. Glaciers are found on some of the higher mountain peaks. The Olympic Mountains are closer to Puget Sound than is the Cascade Range. On the north, a relatively narrow strip of lowlands is between the Olympic Mountains and the Strait of Juan de Fuca. On the east, the mountains directly abut Hood Canal. The rivers discharging from the Olympic Mountains, therefore, tend to be shorter and have smaller drainage areas, less discharge, and steeper average stream gradients than do the rivers

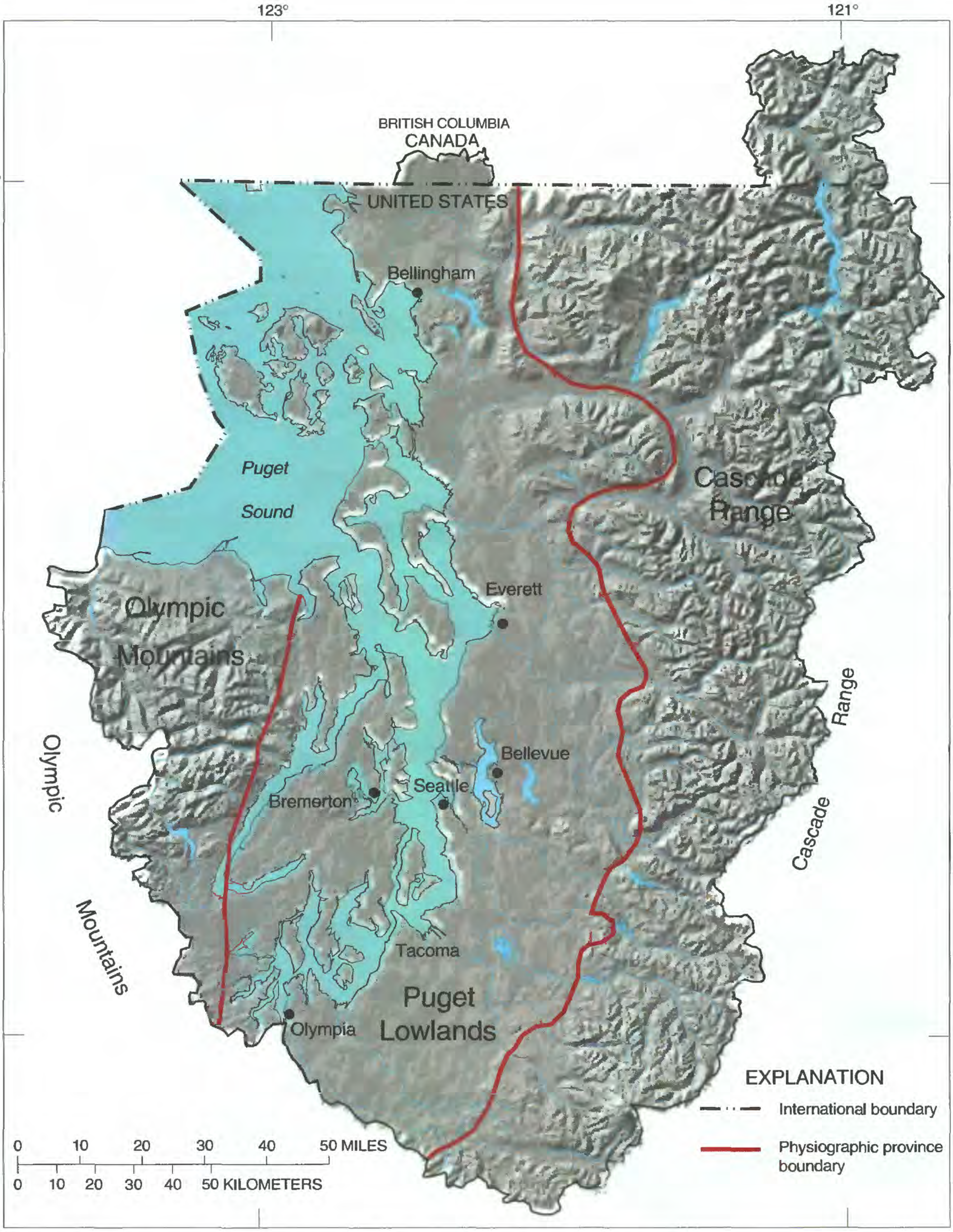


Figure 2. Physiography of the Puget Sound Basin. (Vertical relief exaggerated by a factor of 3.)

discharging from the Cascade Range. The close proximity of the Olympic Mountain front to the Puget Sound also limits the supply of flat land; and with the exception of the lower Dungeness River Basin, this has restricted settlement and land development on the Olympic Peninsula.

Most settlement and development has occurred in the Puget Sound Lowland, owing to its gentler topography and proximity to Puget Sound. Land surface altitude seldom exceeds 500-600 feet in the lowland, with the notable exception of bedrock outcrops that form low-relief mountains and hills in San Juan, Kitsap, and southwestern Whatcom Counties. The Puget Sound Lowland is a structural basin filled to a depth of more than 3,000 feet with alluvial, glacial, and interglacial unconsolidated sediments. The glacial drift was deposited during four major advances and subsequent retreats of the continental (Cordilleran) ice sheet over the past 1 million years, and to a much lesser extent by alpine glacial advances originating in the Cascade Range and the Olympic Mountains. The present surficial geology and landforms of the Puget Sound Lowland are largely the result of the last advance of the Cordilleran ice sheet during the Vashon Stade about 18,000 years ago, and its subsequent retreat.

Following the retreat of the ice sheet and in previous interglacial periods, the major rivers emanating from the Cascade Range and Olympic Mountains transported large quantities of sediment. Much of this sediment was eroded coarse-grained glacial drift and was deposited as alluvium along the major river courses in the lowland valleys and their mountain valley extensions. Alluvial deposits and mudflows fill these valleys to a depth of as much as 600 feet and form large deltas and tidelands where the rivers meet the Puget Sound. Mudflows originate from the major stratovolcanoes in the region and they flow downward as far as Puget Sound following the major river courses. Mount Rainier has produced many large debris flows and debris avalanches during the past 10,000 years. These flows have traveled more than 60 miles from the volcano to inundate parts of the now-populated Puget Sound Lowland (Scott and others, 1995).

The Puget Sound Lowland today is characterized by a low-relief upland plateau of glacial drift that is incised by broad alluvial valleys of the major rivers and by numerous channels, bays, and inlets of Puget Sound and its adjacent waters. Excluding large lakes, the 7,183 mi^2 of unconsolidated deposits present at the land surface in the lowland (fig. 3) consist of 1,570 mi^2 of alluvium, 3,320 mi^2 of fine-grained deposits (mainly glacial till and some glaciomarine drift), and 2,293 mi^2 of coarse-grained deposits (mainly recessional and advance outwash) (Vaccaro and others, in press).

The upland plateau has a surface of rolling hills and is dotted with small lakes and marshy depressions. The plateau has a gentle relief that allows construction of roads and buildings making it generally suitable for development. The sides of the plateau form steep hills or bluffs that descend to alluvial valleys or to Puget Sound. These side slopes have a relief of up to several hundreds of feet, they can be highly erodable and unstable, and they have been incised by steep ravines that have been cut by streams draining the uplands.

The islands of Puget Sound, south of Deception Pass, are composed of glacial drift and have topography similar to the upland plateau of the mainland. The San Juan Islands north of Deception Pass are largely made up of bedrock and are mantled by glacial drift over about one-half of their area.

Geology

Bedrock is exposed at the surface in more than one-half of the Puget Sound Basin, largely in the Olympic Mountains and Cascade Range (fig. 3). The forces that built these mountains uplifted and exposed many different rock types (fig. 4). These rocks are of volcanic, igneous, intrusive, metamorphic, and marine and continental sedimentary origin, ranging in age from less than 1 million to more than 400 million years old.

The Olympic Mountains are generally younger (20-60 million years old) and geologically less complex than the Cascade Range. The Olympic Mountains have a core of metamorphosed and marine sedimentary rocks that are largely composed of graywacke with some interbedded slate and sandstone. This core is surrounded by a band of volcanic rocks that are largely composed of dark gray basalt, forming the eastern slope and foothills of the Olympic Mountains in the Puget Sound Basin.

The Cascade Range is separated into northern and southern parts by a major northwest-southeast structural break in the vicinity of Snoqualmie Pass, southeast of Seattle (Lasmanis, 1991). The north Cascades are older and structurally and mineralogically more complex than the south Cascades. The north Cascades are composed predominantly of intrusive igneous crystalline and

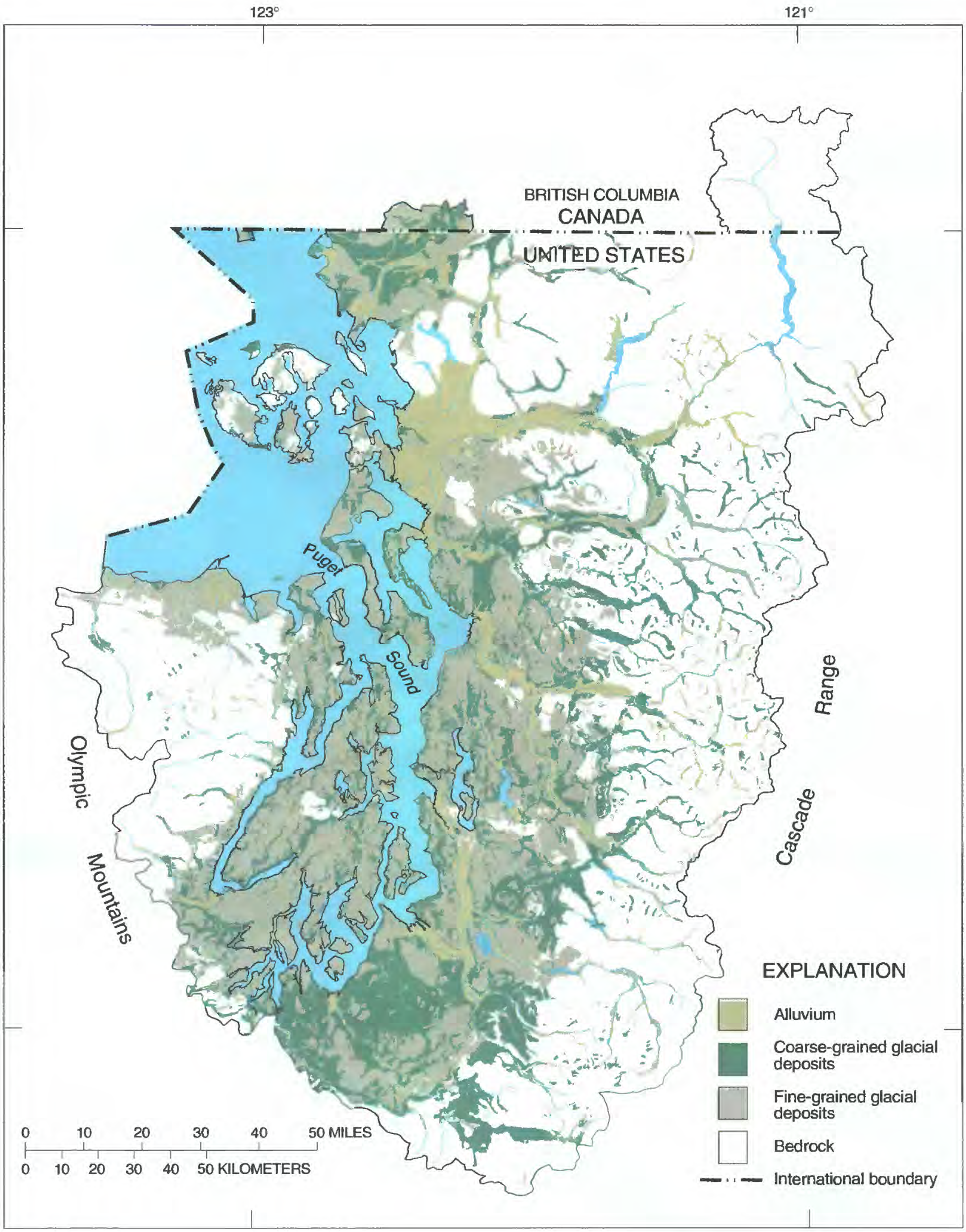


Figure 3. Generalized surficial geology of the Puget Sound Basin. (Modified from Vaccaro and others, in press.)

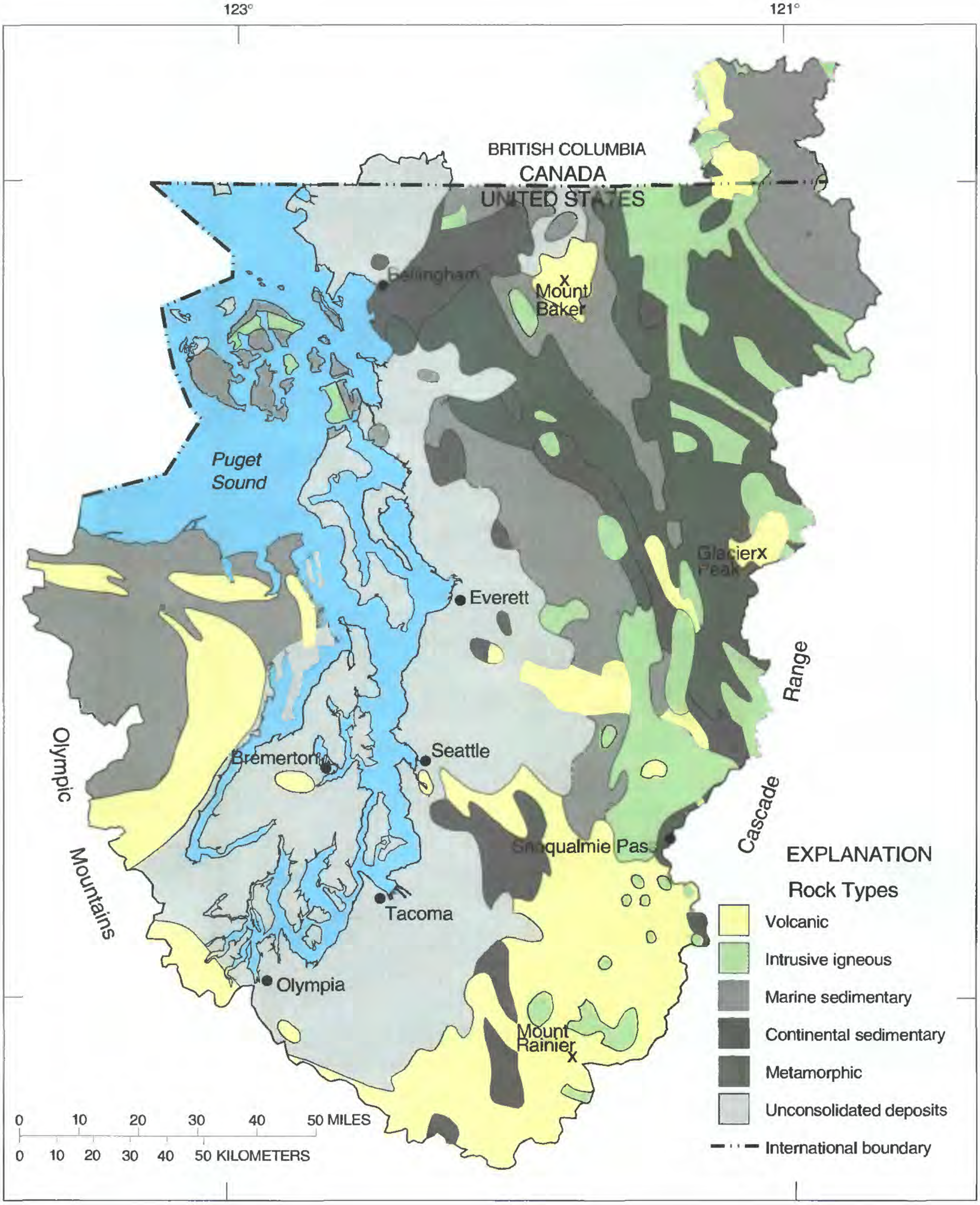


Figure 4. Bedrock geology of the Puget Sound Basin. (Modified from King and Beikman, 1974)

metamorphic rocks such as granite, greenschist, and dunite (Hutting and others, 1961) that range in age from 350 to 400 million years old. Relatively resistant to weathering, these rocks form the rugged peaks of the north Cascade crest.

Two stratovolcanos, Mount Baker and Glacier Peak, are atop the north Cascade crest. These volcanic cones are composed of basalt and include andesite flows and pyroclastic rocks estimated to be less than 1 million years old. After Mount St. Helens, Mount Baker is the most active volcano in Washington State, as demonstrated by gas and steam emissions that occurred in the 1970's.

The north Cascades also have scattered remnants of tuffs, volcanic breccia, and sedimentary rocks. These rocks are arranged in a complex pattern as unrelated terrains or rock groupings that have been brought in contact by strike-slip and thrust faults. The thrust regime extends to the west into the San Juan Islands of the Puget Sound Lowland (Lasmanis, 1991).

This assemblage of rocks contains a variety of mineral resources. Copper, gold, silver, antimony, chrome, lead, and zinc have all been mined in the past, but little mining for metallic minerals occurs today. Most mining today produces nonmetallic minerals such as sand, gravel, clay, cement, and stone, which are produced in quantity for the construction industry (Pacific Northwest River Basins Commission, 1970a).

The south Cascades consist predominantly of volcanic rocks such as basalt and andesite that range in age from 2 to 60 million years old and smaller associated deposits of volcanoclastics, lahars, ash beds, and mudflows. The south Cascades lack the structural complexity of the north Cascades and contain fewer minerals of economic value. However, in the south Cascade foothills and along the eastern margin of the Puget Sound Lowland, east of the Seattle-Tacoma metropolitan area, coal beds are interspersed with nonmarine shales, siltstones, and sandstones of the Puget group. These coal beds were extensively mined around the turn of the century, producing as much as 4 million tons of coal per year. The deep mines have all shut down, and only one open pit coal mine, located in southeastern King County, operates today.

The most notable feature of the south Cascades is Mount Rainier, a stratovolcano. At 14,410 feet, it stands about 7,000 feet above the south Cascade crest. Mount Rainier began forming as a pyroclastic cone about 1 million years ago and substantially increased in size from voluminous andesite flows about 700,000 years ago. Mount Rainier is still considered an active volcano as several small eruptions were reported between 1820 and 1894 (Lasmanis, 1991).

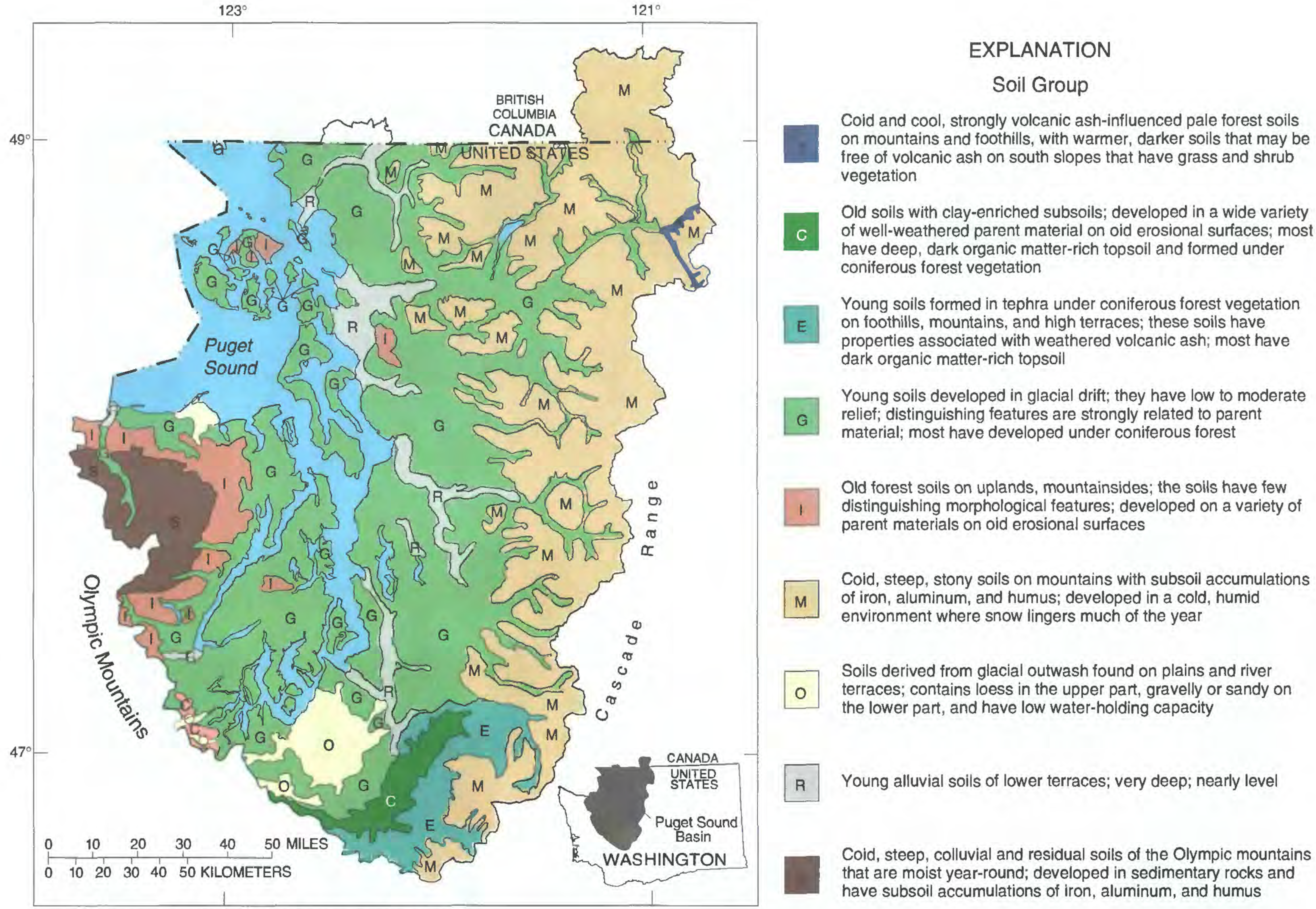
Bedrock outcrops are few in the Puget Sound Lowland, but they do exist along the Seattle-Bremerton structural high and in the San Juan Islands and the Chuckanut Mountain area in the northern Puget Sound Basin. These outcrops are composed largely of sedimentary rocks such as limestone, argillite, shale, and siltstone. There are some coal interbeds in the Chuckanut formation south of Bellingham and in the Puget group southeast of Seattle, and volcanic rocks occur in the hills of Kitsap County to the west of Bremerton.

Soils

Most soils in the Puget Sound Basin are relatively young, having been formed over the last 10,000 to 12,000 years since the retreat of the continental ice sheet. These soils generally were formed under coniferous forests from parent material of bedrock in the higher altitudes, glacial drift in the lowlands and lower mountain slopes, and more recent alluvial deposits along the major river valleys. The depth and complexity of the soil profiles vary greatly, depending on the nature of the parent material, the landscape relief, altitude, and vegetation. Over 200 soil series have been formally identified in the Puget Sound Basin, and these series have been informally organized into nine groups as shown in figure 5 (U.S. Soil Conservation Service, 1993a).

The Cascade Range soils of group M in figure 5 are steep and stony soils that have developed in a cold, humid environment under coniferous forest and, above the timber line, on mountain slopes where snow lingers much of the year. Soils in the northern Cascade Range are formed from predominantly igneous and fine-grained metamorphic rocks and from andesite, volcanic pumice, and ash along the slopes of the volcanic peaks. South of Snoqualmie Pass, soils are formed from predominantly volcanic rocks and from tephra near Mount Rainier. Soils in the Cascade Range tend to be acid, infertile, and poorly developed, but they do support extensive coniferous forests in the lower to middle altitudes.

The Olympic Mountain soils of groups S and I were formed from sedimentary rocks and basalt. Soils of group S are found in the higher altitudes, and they are steep, stony colluvium. The soils of group I are found on the lower slopes and foothills of the Olympic Mountains and tend to be finer grained, loamy to silty.



Soil associations modified from U.S. Soil Conservation Service, 1993a.

Figure 5. Generalized soils map of the Puget Sound Basin.

On the slopes of both the Olympic Mountains and the Cascade Range, soils are commonly formed in a mixture of glacial till and residual colluvium and are often unstable and subject to creep or landslides. The stability of mountain soils is of concern because logging-roads and timber harvesting can contribute to slope instability and increase the frequency and amount of landslides. Landslides into stream channels can add large amounts of sediment to streams and degrade the habitat of aquatic species.

The soils of the Puget Sound Lowland were formed largely from glacial drift, as represented by groups G and O, or from alluvium, as represented by group R. Small areas of soils represented by group I also are found in isolated areas of San Juan, Kitsap, and Skagit Counties, where bedrock crops out above the glacial drift. Soils represented by group G are found on the hills and upland plateaus and cover a large area of the Puget Sound Lowland. These soils generally were formed from silty or sandy clay till under a coniferous forest cover. They tend to be organically rich in the surface horizon, but are acidic and nutrient poor in the underlying horizons. The surface horizons are also well weathered and relatively permeable, and the underlying till can be compact and weakly cemented and can impede drainage. These soils tend to be stable and suitable for building on all but the steepest slopes, and they have been extensively built upon in the central Puget Sound region in the Seattle-Tacoma metropolitan area. Soils represented by group G are not considered prime agricultural soils and have not been developed extensively for agricultural purposes, although they have been used as pasture land and less commonly for growing small grains. Group G soils also often have severe limitations for septic tank fields because of poor drainage through the cemented till (U.S. Soil Conservation Service, 1979).

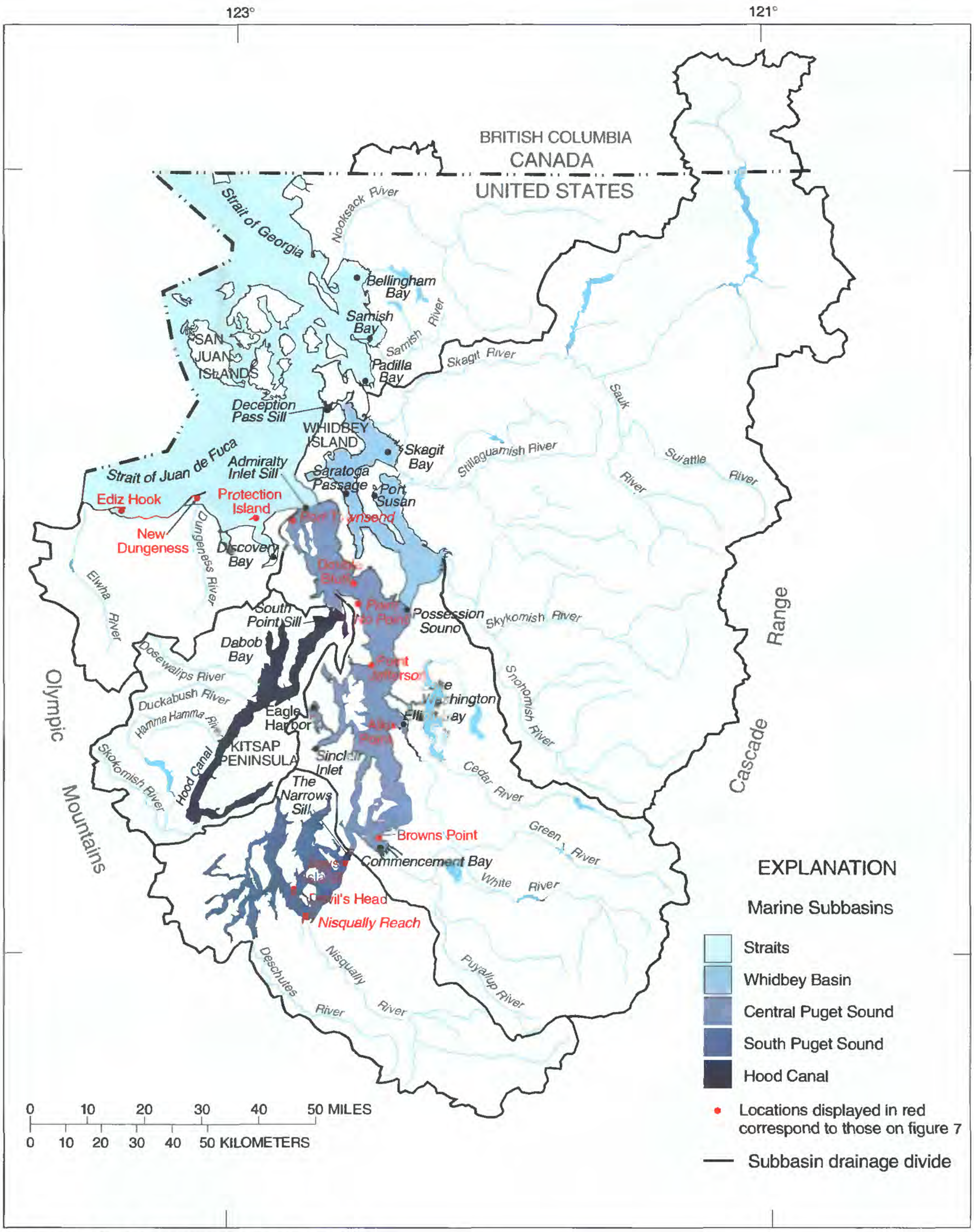
Soils formed on glacial outwash are represented by group O. These soils are characterized as coarse, well drained, and flat. They tend to have a thin, organically rich surface horizon and are vegetated by grass and ferns. These soils are found in southern Puget Sound Basin below Tacoma on the broad, flat, grassy outwash plains known locally as prairies. These soils are very permeable, and the underlying surficial aquifers are potentially vulnerable to contamination.

Soils represented by group R are found on the broad, flat floors of the alluvial valleys. These soils were formed from stream channel and overbank flood deposits. The soils tend to be finer and more fertile in the lower parts of the stream valleys, trending from sandy and silty in the upper- and middle-lowland valleys to clayey downstream in the river deltas. In the upper and middle valleys, there is also a textural trend laterally across the valley with coarse sandy soils near the stream channels trending to sandy and silty soils toward the outer valley perimeter. Group R soils are prime agricultural soils and have been extensively developed for producing high-value agricultural products such as row crops, nursery stock, berries, and cut flowers. The fine-grained soils of the river deltas are among the most fertile in the study unit, but in their natural state, they are subject to a seasonally high water table and frequent winter flooding. To make these soils suitable for farming, large areas of the river deltas have been drained by extensive networks of ditches, and dikes have been built along rivers and streams to protect these lands from flooding, particularly in the Skagit, Nooksack, and Snohomish River deltas. The Duwamish and Puyallup River deltas have also been channelized and diked to allow development of industrial and port facilities. Drainage, diking, and filling of group R soils to improve their value for agriculture and industry have resulted in the loss of large wetland areas both in the river deltas and along the stream channels of the alluvial valleys. An estimated 70 percent of tidally influenced wetlands have been lost in the Puget Sound Basin (Bortleson and others, 1980, and Puget Sound Water Quality Authority, 1992).

Puget Sound

Puget Sound is a semi-enclosed glacial fjord that is considered part of one of the largest estuaries in the world (Puget Sound Water Quality Authority, 1988). Although the saltwater bodies of Puget Sound are not a part of the NAWQA study unit, it is important to understand the physical structure and circulation pattern of Puget Sound and its ability to flush or assimilate contaminants to fully assess the significance of contaminant discharges from the study unit.

Together with the adjacent waters of the Strait of Juan de Fuca and the Strait of Georgia, Puget Sound encompasses an area of 3,200 mi^2 and has a 2,250-mi (mile) coastline within the study unit (fig. 6). Puget Sound encompasses all waters south of Admiralty Inlet and Deception Pass, where shallow sills separate Puget Sound from the deeper waters of the Strait of Juan de Fuca and the Strait of Georgia. The Strait of Juan de Fuca and the Strait of Georgia are two distinct water bodies separated by a ridge surfacing as the San Juan Islands. Marine waters flow from Puget Sound proper and the Strait of Georgia through the Strait of Juan de Fuca and out to the Pacific Ocean.



Modified from Puget Sound Water Quality Authority, 1988.

Figure 6. Major marine subbasins and associated subbasin drainage divides in Puget Sound.

The mixing of freshwater inflows with salt water from the Pacific Ocean results in an average salinity of 27 parts per thousand in Puget Sound (Puget Sound Water Quality Authority, 1988). The average depth of Puget Sound at mean low tide is 205 feet. Combined with the region's mild climate and tidally driven mixing with Pacific Ocean waters, the sound has relatively stable, cool water temperatures throughout the year. The average surface-water temperature ranges between 45 °F (degrees Farenheit) in the winter and 55 °F in the summer.

Puget Sound is composed of a complex, interconnected system of four main subbasins: central Puget Sound, south Puget Sound, Hood Canal, and Whidbey Basin (fig. 6). Submarine sills ranging in depth from 145 to 218 feet define these subbasins and play an important role in the circulation pattern of the Sound. Central Puget Sound is the largest and deepest of these subbasins. It contains roughly 60 percent of the total water volume in the sound (Puget Sound Water Quality Authority, 1992) and ranges in depth to 930 feet just off Point Jefferson. Central Puget Sound receives an average of 8,600 ft^3/s (cubic feet per second) (Williams, 1981) of freshwater inflow from the Puyallup, Green-Duwamish, and Cedar-Lake Washington River Basins as well as most of the stormwater runoff and wastewater discharges from the Seattle-Tacoma metropolitan area. Many shellfish beds in central Puget Sound have been closed to harvest due to contamination by fecal bacteria, which may originate from land-based point and nonpoint sources.

South Puget Sound has many shallow bays and inlets and receives an average of 3,200 ft^3/s of freshwater inflow from the Nisqually and Deschutes Rivers and several smaller lowland streams (Williams, 1981). Hood Canal is a relatively deep, narrow channel that receives an average of 5,000 ft^3/s of freshwater inflow, mainly from streams draining the eastern Olympic Mountains. The Whidbey Basin receives about 30,700 ft^3/s of freshwater inflow (over one-half of the total Puget Sound Basin freshwater discharge) from the Skagit, Stilliguamish, and Snohomish River Basins (Williams, 1981). These three subbasins are important areas for harvesting shellfish (clams, oysters, and mussels) and are vulnerable to contamination by fecal bacteria.

As a northern-latitude fjord, Puget Sound experiences a large tidal range. The average daily difference between high and low tide in Puget Sound ranges from 8 feet near Port Townsend to 15 feet in Olympia, and these tides result in a large exchange of water between Puget Sound, the straits, and the Pacific Ocean. The average tidal prism in Puget Sound is 1.27 mi^3 (cubic miles), or about 3.2 percent of the 40.3-mi^3 total high tide volume of Puget Sound (Puget Sound Water Quality Authority, 1988).

Estuarine circulation in Puget Sound is propelled by tidal activity, gravitational forces, and freshwater inflows and is complicated by the irregular coastline and submarine topography of Puget Sound and by the density difference between freshwater and salt water. As freshwater enters the sound, it is less dense and lighter than the incoming salt water, and therefore flows near the surface and becomes brackish as it partially mixes with salt water. This approximately 200-feet-deep brackish layer flows seaward over the heavier ocean salt water being drawn inland (fig. 7). Some degree of mixing occurs as the incoming salt water is forced upward at the sills, and in the mixing zone, some of the outgoing brackish water is taken to depth and recirculated back into the subbasin. It is estimated that freshwater flowing into central Puget Sound averages about two recirculation cycles before making it out through the Strait of Juan de Fuca (Puget Sound Water Quality Authority, 1988). This recirculation partially inhibits flushing in Puget Sound, and it is estimated that, on the average, waters in the central Puget Sound are replaced at the rate of twice per year, and the waters of Hood Canal and south Puget Sound are replaced at the rate of only once per year (Puget Sound Water Quality Authority, 1988).

The flushing of Puget Sound removes or dilutes dissolved contaminants and inhibits them from accumulating to problematic levels. With the exception of some of the shallow southern bays and inlets, most of Puget Sound is not greatly affected by excessive nutrient levels and eutrophication due to its depth, cool temperature, and high rate of tidal flushing. However, the presence of the sills and the recirculation of water effectively traps most suspended material that enters Puget Sound. A recent study estimated that only 1 to 5 percent of the sediment particles initially present in freshwater discharging into the central Puget Sound Basin are carried past Admiralty Inlet (Puget Sound Water Quality Authority, 1988). Sediment deposits at an estimated rate of 0.18 to 1.2 grams per square centimeter per year on the bottom of the central Puget Sound Basin. Since many contaminants bind to sediment particles, accumulation of contaminants in the bottom sediments of Puget Sound is a concern, particularly in urban bays, which are close to the source of most contaminants.

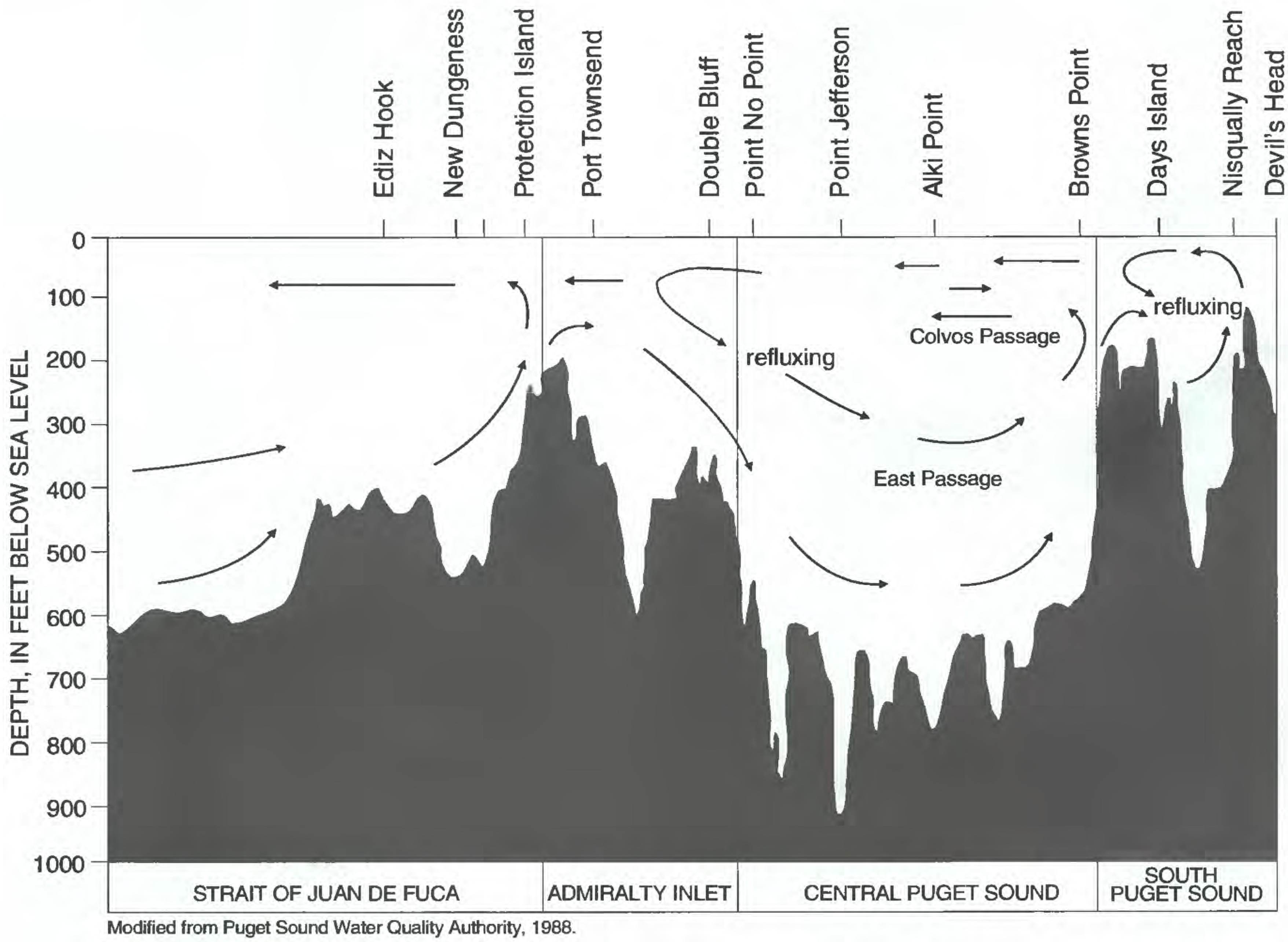


Figure 7. Generalized vertical section showing salt water circulation patterns in the Puget Sound trough.

Climate

The Puget Sound Basin has a middle-latitude marine climate, which is influenced primarily by the Pacific Ocean and the presence of two major mountain ranges. The Pacific Ocean, which is warmer in the winter and cooler in the summer than the adjoining land, has a moderating effect on the regional climate as semipermanent high and low pressure cells over the North Pacific propel a consistent supply of mild, moisture-laden marine air into the basin. The high-pressure cell moves north from the California coast in the spring and blocks most Pacific storms from reaching the basin in the summer, resulting in warm, dry weather. During the fall, the high-pressure cell weakens and is replaced by a low-pressure cell that moves south from the Gulf of Alaska, allowing a steady stream of Pacific storms to reach the basin throughout the winter. Spring and fall are periods of transition between the dominant high- and low-pressure systems, and the weather is variable. The Cascade Range on the east side of the basin further moderates the climate by acting as a barrier to most cold arctic air masses in the winter and buffering against warm summer continental air. In the west, the Olympic Mountains partially protect the region from severe Pacific winter storms. The result is a year-round temperate climate with a dry summer and a mild but rainy winter.

Temperature

Temperatures in the Puget Sound Basin are fairly mild throughout the year. Summer temperatures are tempered by cool oceanic winds and winter temperatures are moderated by persistent cloudiness. Annual warm and cold temperature extremes occur when the region falls under the influence of a continental rather than the normal marine air mass. This shift generally occurs for only a few days at a time and results in cold, clear days in the winter and hot, dry days in the summer with easterly winds predominating.

Mean annual temperature in the Puget Sound Lowland ranges between 50 and 60°F, and average daily temperatures range from 60 to 80°F in the summer to between 30 and 50°F in the winter (Vaccaro and others, in press). Temperatures measured at the Sedro Wooley weather station in the northern part of the Puget Sound Basin are typical of the lowlands (fig. 8). The warmest months are July and August, with average monthly temperatures of 62 and 63°F, respectively, and daily highs ranging between 70 and 85°F. Altitude, proximity to water, and north-south positioning can effect local temperatures. Coastal areas north of Puget Sound such as Port Townsend, receive cool ocean breezes and consequently have cooler summer temperatures, and southern, inland areas, such as Olympia, tend to have warmer temperatures.

Average daily winter temperatures in the lowlands generally stay above freezing. Average monthly temperatures in Sedro Wooley are approximately 41°F in December and 39°F in January, but daily minimum temperatures often reach the mid-teens. The lowlands average 20 to 90 nights per year and 10 to 20 days per year with temperatures below freezing (Vaccaro and others, in press). In Port Townsend, winter temperatures tend to be slightly warmer because of its proximity to the Pacific Ocean and average 42 and 41°F in December and January, respectively. Farther inland, near Olympia, mean monthly temperatures are slightly cooler in winter, averaging 38°F in December and January.

Temperature in the Puget Sound Basin gradually decreases as altitude increases (fig. 8). Mean annual temperatures in the mountains range between 30 and 50°F, depending primarily on altitude, although slope, exposure, shading, and snowpack result in local temperature variability. Mean monthly temperatures range between 55 and 65°F in July and August, and 20 and 40°F in December and January. Average monthly temperatures at Cedar Lake (altitude 1,560 feet) are 61°F in August, and 35°F in January. Stampede Pass (altitude 3,860 feet) is considerably cooler, with average monthly temperatures of 56°F in August and 24°F in January. In general, average daily winter temperatures in the mountains range between 20 and 40°F, and winter nighttime temperatures generally stay below freezing.

Precipitation

Excluding the saltwater areas, mean annual precipitation for the Puget Sound Basin is approximately 74 in/yr (inches per year) (Vaccaro and others, in press). Mean annual precipitation in the lowlands averages about 40 in/yr, ranging from just over 16 inches near Sequim in the rainshadow of the Olympic Mountains, to almost 47 inches at Sedro Wooley (fig. 9). In the Olympic and Cascade foothills, precipitation ranges between 45 and 60 in/yr, with the larger quantities occurring in the Olympic foothills. Precipitation in the mountains averages about 90 in/yr but can range widely from 60 in/yr to more than 200 in/yr, depending on altitude and orientation to prevailing storm tracks. The wettest areas in the basin are found on the western slopes of the Cascade

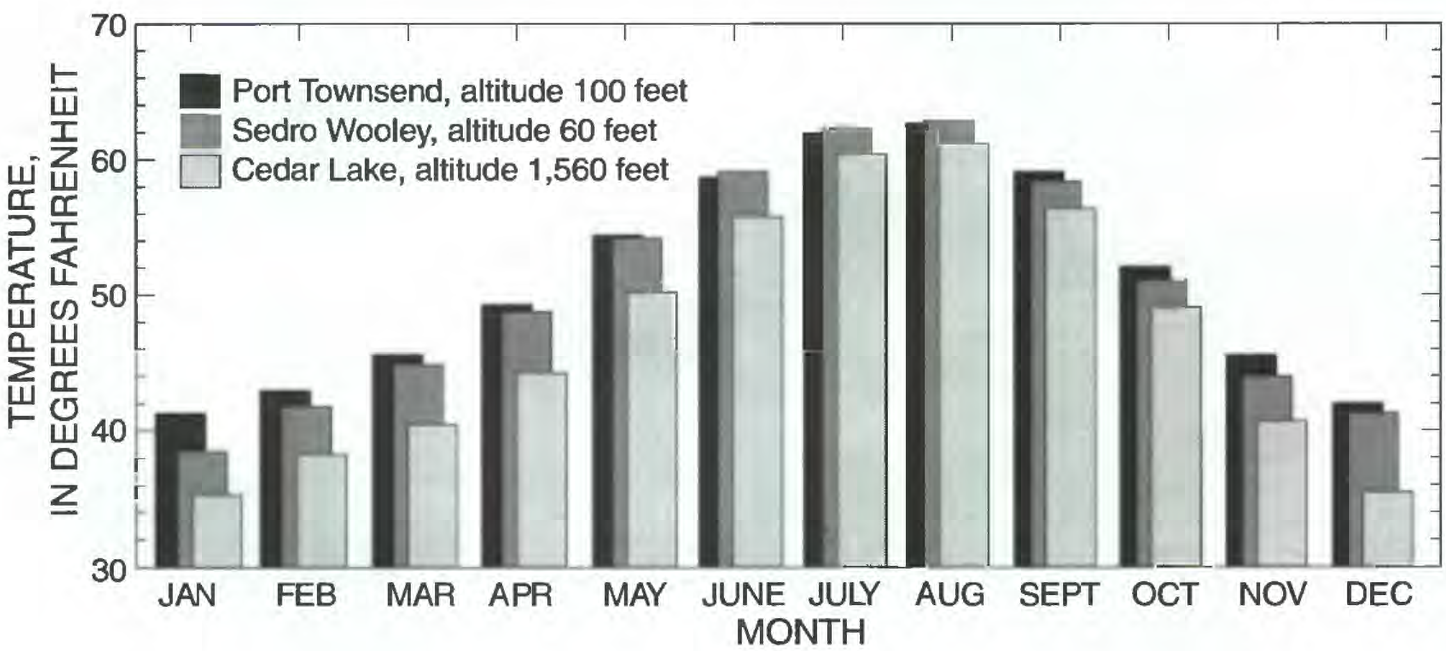
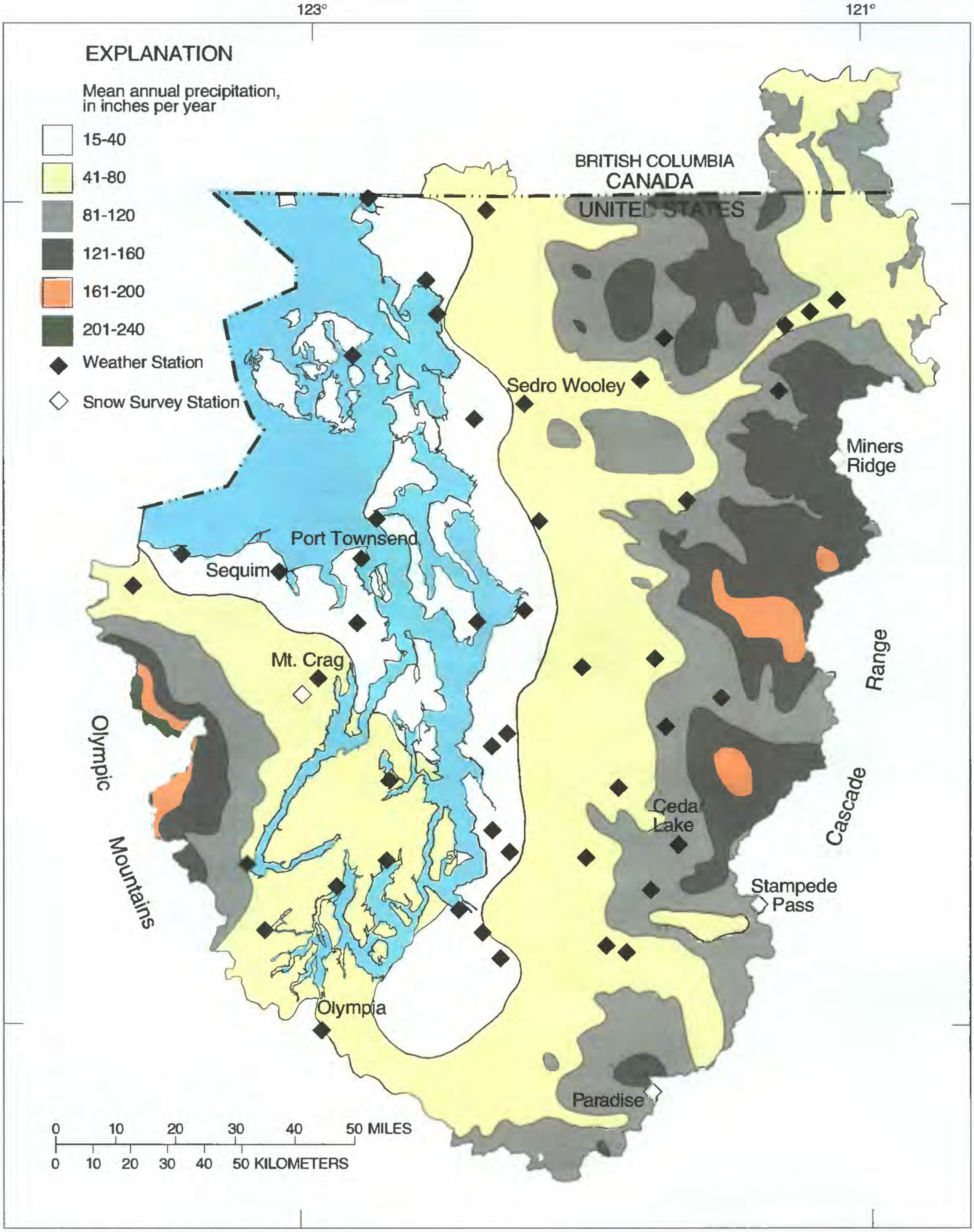


Figure 8. Average monthly temperatures (1961-1990) at three weather stations in the Puget Sound Basin. (Data from National Oceanic and Atmospheric Administration, 1993.)



Precipitation contours modified from (Vaccaro and others, in press).
Weather station locations from National Oceanic and Atmospheric Administration, 1993.

Figure 9. Precipitation contours, weather station locations, and selected snow survey stations of the Puget Sound Basin.

Range and the upper altitudes of the Olympic Mountains, where orographic lifting strips moisture from the ascending ocean air.

The Puget Sound Basin generally receives a reliable supply of winter precipitation. Yearly variations in precipitation may seem large, but the percentage of deviation from normal is modest, and long-term effects are minimal. During the 20-year period of 1973-1992 at Cedar Lake, for example, the driest year occurred in 1985, when the station recorded a 38-inch deficit from normal, or a 37 percent shortfall, but the station still received more than 64 inches of precipitation. In contrast, the wettest year occurred 5 years later in 1990 when Cedar Lake recorded 131.7 inches of precipitation, an excess of 29.7 inches or a 29 percent deviation from normal. Sequim, a station that averages only 16.5 inches of precipitation per year, recorded extremes of 10.9 in 1973 and 20.2 in 1990, respective deviations of 34 percent and 22 percent from normal (fig. 10).

Although the Puget Sound Basin generally receives an ample supply of annual precipitation, it is unevenly distributed between a wet winter and a dry summer. The summer dry season typically begins around May and extends to early October, when the basin receives only about 20 percent of its annual precipitation. July and August are the driest months during which the basin receives only 5 percent of the area's annual precipitation, most of which is lost to evapotranspiration. It is not unusual for 2 or 3 weeks to pass in the summer without a trace of precipitation.

The rainy season usually begins in late October, reaches a peak in December or January, and gradually decreases through the spring (fig. 11). Approximately 80 percent of the region's precipitation falls during October to April. Winter precipitation from the predominant cool air masses originating in the Gulf of Alaska tends to be light to moderate in intensity. More intense precipitation occurs occasionally, from southwesterly winds that bring warm, moist air northward from the tropics near Hawaii. These warm winter rains can fall as continuous downpours, resulting in heavy runoff and significant flooding.

Extreme storms in the Puget Sound Basin have reasonably well defined seasonal characteristics as described by Schaefer (1989). Intense storms of short duration (2 to 5 hours) occur predominantly in the warm season, from May through October. Rainfall quantity for these short storms can amount to 1 inch in the lowlands and 1.4 inches in the mountains. Twenty-four hour extreme storm events occur mostly in the winter months between October and March. These storms can bring up to 4.2 inches of rain to the lowlands and 6.2 inches to the mountains.

Snow and Ice

As winter marine air is swept inland, it has a temperature near that of the ocean's surface, but it cools as the air rises to pass over the Olympic Mountains and Cascade Range. Winter precipitation therefore falls primarily as rain in the lowlands, as a mix of rain and snow in the foothills (from 1,000 to 3,000 feet above sea level), and as snow in the mountains above 3,000 feet. Seasonal snowfall ranges from 10 to 30 inches in the lowlands, 75 to 100 inches in the foothills, and 300 to 500 inches in the mountains above 3,000 feet (Kruckeberg, 1991). In the snow-transition zone (1,000 to 3,000 feet), where average temperatures fluctuate around freezing, precipitation alternates between rain and snow, and the snowpack is highly variable. In the mountains above 3,000 feet, 80 percent of the precipitation falls as snow, which typically covers the ground from November to May. The depth of the mountain snowpack tends to peak in early April. Typical snow-water equivalent measurements at the SNOTEL (U.S. Soil Conservation Service, 1993b) weather stations in early April are 68 inches at Paradise, 44 inches at Stampede Pass, and 30 inches at Mount Crag (fig. 12). The snow pack tends to melt rapidly in the late spring as warm, dry weather predominates, and by July, most of the snow is gone. Snowmelt contributes a significant amount of streamflow to the major rivers draining mountain areas.

At the highest altitudes, where the quantity of annual snowfall exceeds average annual snowmelt, glaciers form. There are 386 glaciers covering approximately 116.4 mi^2 in the Puget Sound Basin, occurring predominantly on the stratovolcanos and the highest peaks of the North Cascade Range and Olympic Mountains. The 27 named glaciers on Mount Rainier contain 140 billion ft^3 of ice and constitute the largest glacier system of any peak in the conterminous United States (Driedger and Kennard, 1986). Streams receiving glacial meltwater have well-sustained flows during the dry summer months, when they can carry large loads of fine sediment (glacial flour).

Solar Radiation and Evapotranspiration

The Puget Sound Basin receives little solar radiation during the winter due to its northern latitude and cloudy winter weather, but solar radiation increases greatly during

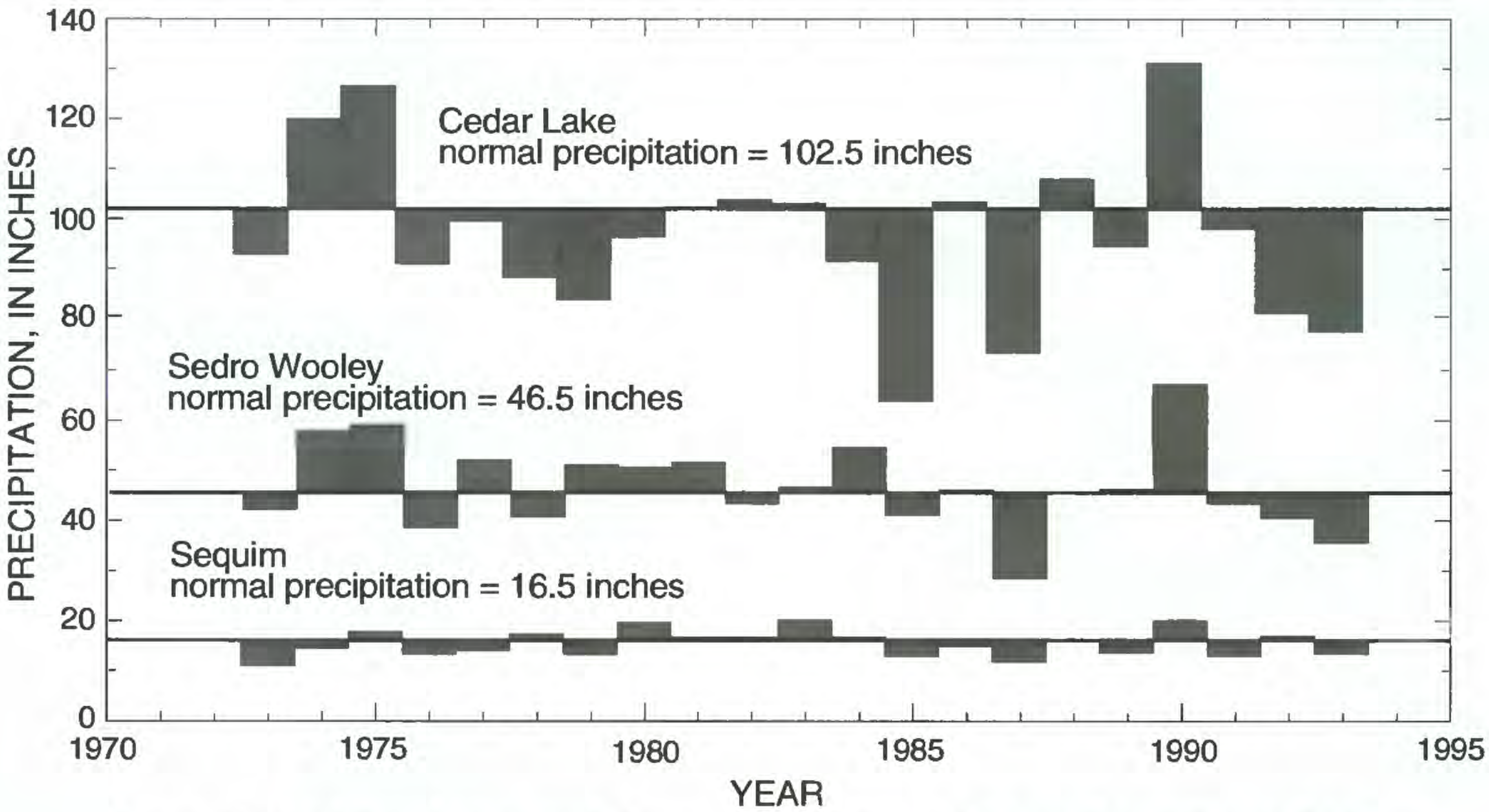


Figure 10. Deviations from normal of annual precipitation at three weather stations in the Puget Sound Basin. (Data from National Oceanic and Atmosphere Administration, 1973-1993; normal annual precipitation, shown as black line, based on period of 1961-1990.)

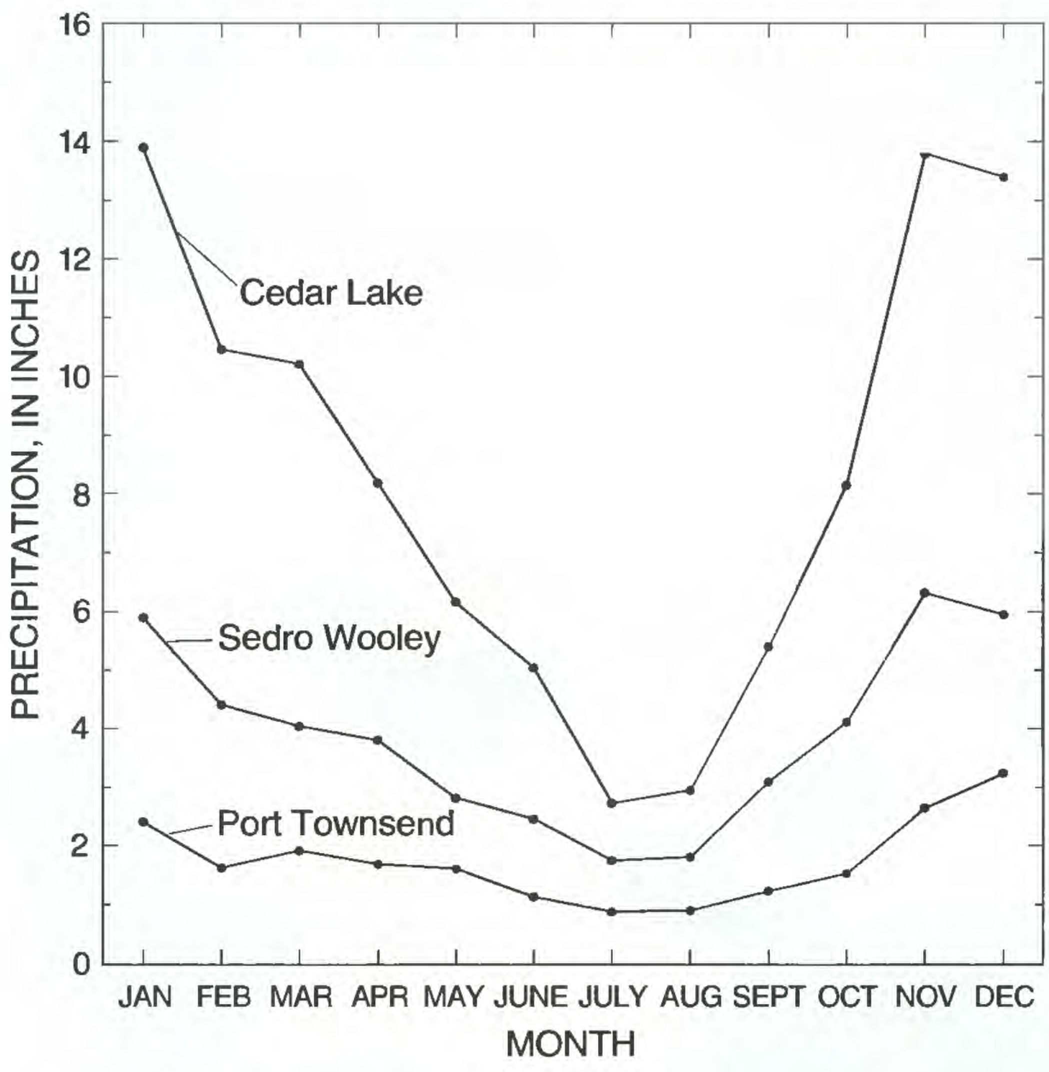


Figure 11. Average monthly precipitation at three weather stations in the Puget Sound Basin. (Data from National Oceanic and Atmospheric Administration, 1973-1993.)

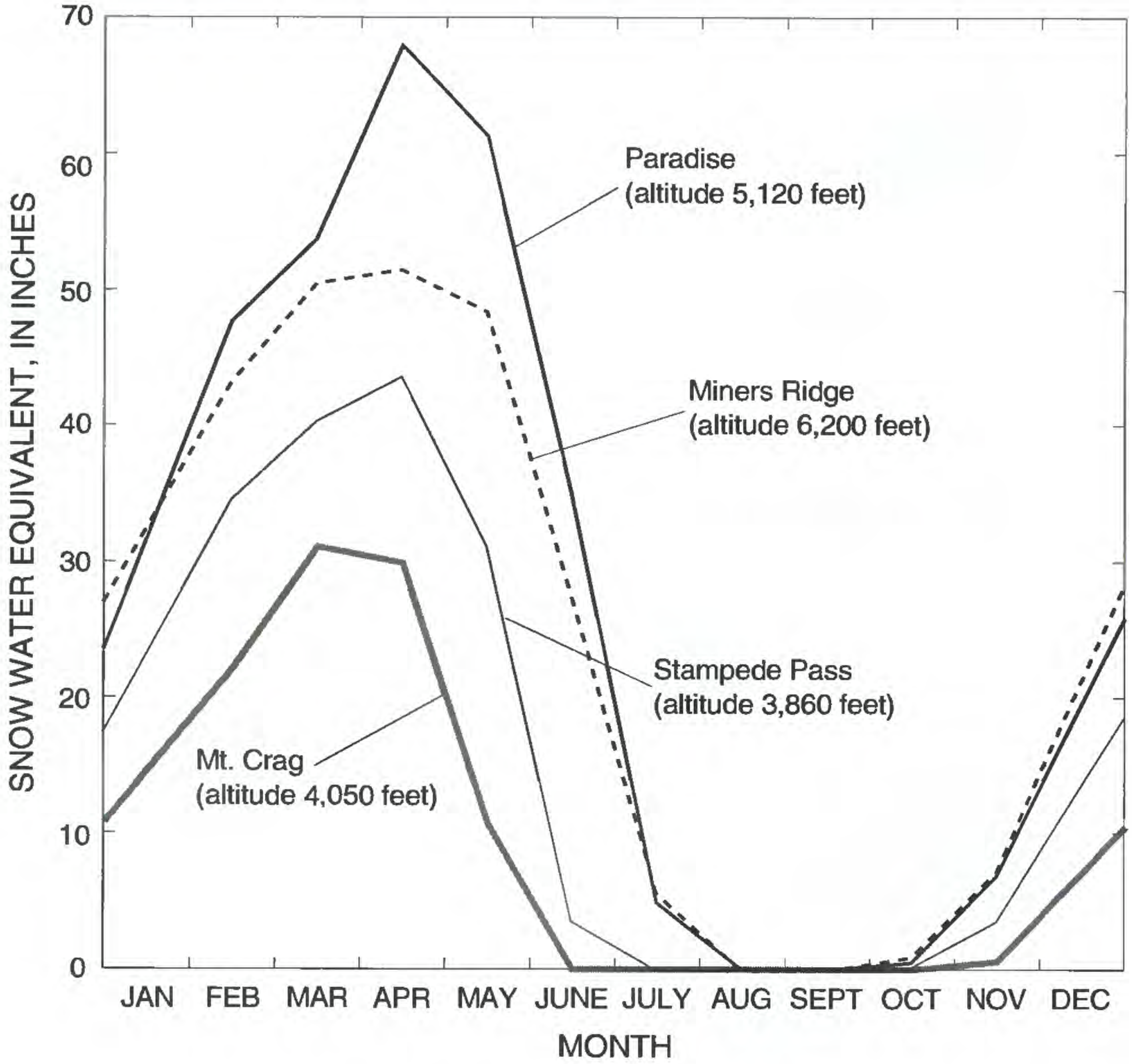


Figure 12. Average monthly snowpack at four sites in the Puget Sound Basin. (Natural Resources Conservation Service SNOTEL data, 1961-1990, United States Soil Conservation Service, 1993b.)

the long, cloud-free summer days. Average daily solar radiation (both direct and diffused) increases from less than 75 langleys in winter to more than 500 langleys in the summer. Solar radiation strongly influences air temperature, evapotranspiration, and the regional water budget. In Seattle, for example, from May through October, when solar radiation and air temperature are the highest, 27 of the 34 inches of annual pan evaporation (an estimator of potential evapotranspiration) occurs; July alone averages 6.8 inches of pan evaporation (Farnsworth and Thompson, 1982). Pan evaporation is greatest during the period in which precipitation is the lowest. During the middle to late summer, the potential evapotranspiration in the lowlands exceeds the amount of precipitation, resulting in seasonal drought conditions. These conditions necessitate the application of irrigation water to agricultural crops, lawns, and ornamental vegetation. With little precipitation available for ground-water recharge or runoff in the middle to late summer, streamflows can become critically low, affecting water quality and aquatic habitat throughout the region.

Surface Water

The quantity, distribution, and variability of streamflow has an important influence on the quality of surface water. The quantity of water in a stream influences its ability to support aquatic life, to assimilate or dilute waste discharges, and to carry suspended sediment. The temporal variability of streamflow is an important cause of the temporal variability of water quality, and knowledge of streamflow is important to understanding the water-quality and ecological dynamics of a watershed.

The Puget Sound Basin is composed of multiple watersheds that drain to Puget Sound and its adjacent waters. These watersheds range in size from the Skagit River Basin, with a drainage area of 3,184 mi^2, to numerous small intermittent streams with drainage areas of only a few acres. Fourteen watersheds have drainage areas greater than 100 mi^2, and together they drain 9,928 mi^2 or 73 percent of the basin. The remaining 3,672 mi^2 or 27 percent of the basin is drained by over 100 smaller watersheds of varying sizes that are clustered in the Puget Sound Lowland and Olympic Mountains along the shores of Puget Sound. Long-term measured streamflow information is available for most of the large rivers and many of their larger tributaries from over 100 stream gaging stations presently operated by the U.S. Geological Survey (USGS) in the Puget Sound Basin. Streamflow information for some of the smaller streams are also available from gaging stations operated by other agencies.

Streamflow

Total average annual surface-water discharge from the Puget Sound Basin is estimated as 52,500 ft^3/s (cubic feet per second) (Williams, 1981). Of this total, 91 percent or 47,900 ft^3/s is discharged by the 14 largest tributaries (fig. 13). With the exception of the Deschutes and Samish Rivers, these large tributaries to Puget Sound have their headwaters in the Olympic Mountains or the Cascade Range and drain high-altitude areas that receive from 50 to more than 200 inches of precipitation annually. These mountain areas can yield an average of over 100 inches of runoff per year (fig. 14), while lowland streams typically yield 20 to 40 inches of average annual runoff, and those in the rainshadow of the Olympic Mountains may yield an average of as little as 10 inches of runoff. The larger rivers have their headwaters in the mountains, which receive a greater amount of precipitation, and therefore yield a proportionately greater quantity of runoff than do the lowland streams. For instance, the Nooksack and Elwha Rivers, which both drain large mountainous areas, respectively yield an average of 66.3 and 75.7 inches of runoff per year, while streams draining the lowlands such as the Deschutes and Samish Rivers respectively yield an average of 27.7 and 37.6 inches of annual runoff (table 1). Annual runoff from the Puget Sound Basin as a whole averages about 52 inches and is among the highest in the nation. Annual runoff from the continental U.S. averages only about 10 inches per year (Pacific Northwest River Basins Commission, 1970b).

Streamflow varies seasonally in response to seasonal variations of precipitation, evapotranspiration, and snowmelt. In the major river basins with headwaters in the mountains, the highest monthly flows generally occur in December and January in response to increased winter rainfall, and in May and June in response to mountain snowmelt. Lowest flows occur in September at the end of the typically dry summer. Williams (1981) estimated that the median monthly discharge to Puget Sound from the principal streams (defined as those with an average annual discharge of 20 ft^3/s or more) is 66,000 ft^3/s in December, 47,000 ft^3/s in March, 67,000 ft^3/s in June, and 22,000 ft^3/s in September. Streamflow in most of the larger rivers draining the Olympic Mountains and Cascade Range generally follows this pattern, but variations, particularly among the smaller streams, occur depending on the altitude of the watershed, presence of glaciers or large snow fields in the headwaters, or flow regulation by reservoirs. For instance, as shown in figure 14, the monthly discharges of the Snoqualmie River and the Duckabush River generally represent the seasonal flow pattern of unregulated rivers draining the Cascade Range and

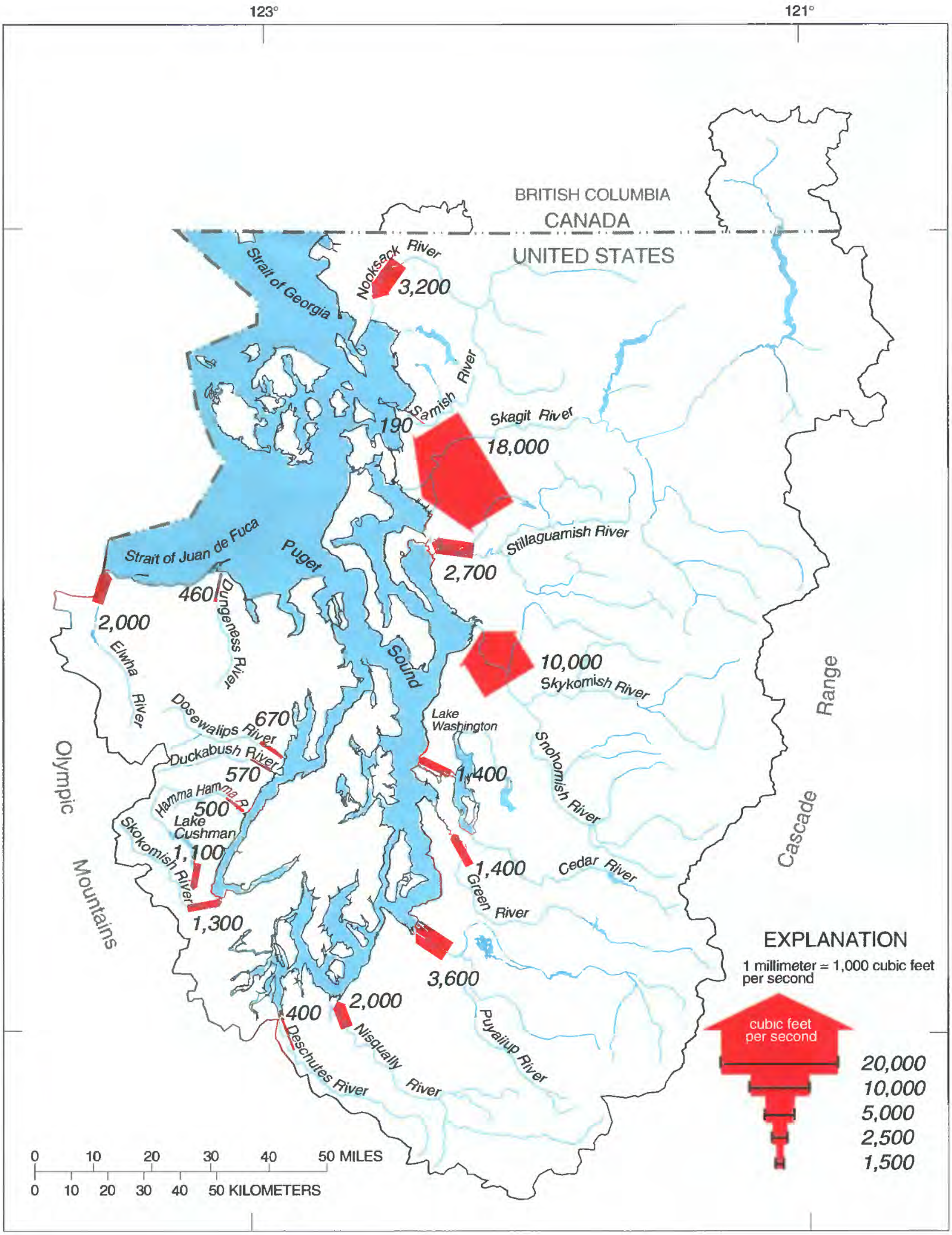


Figure 13. Mean annual discharge of major rivers in the Puget Sound Basin. (Data in cubic feet per second, from Williams, 1981.)

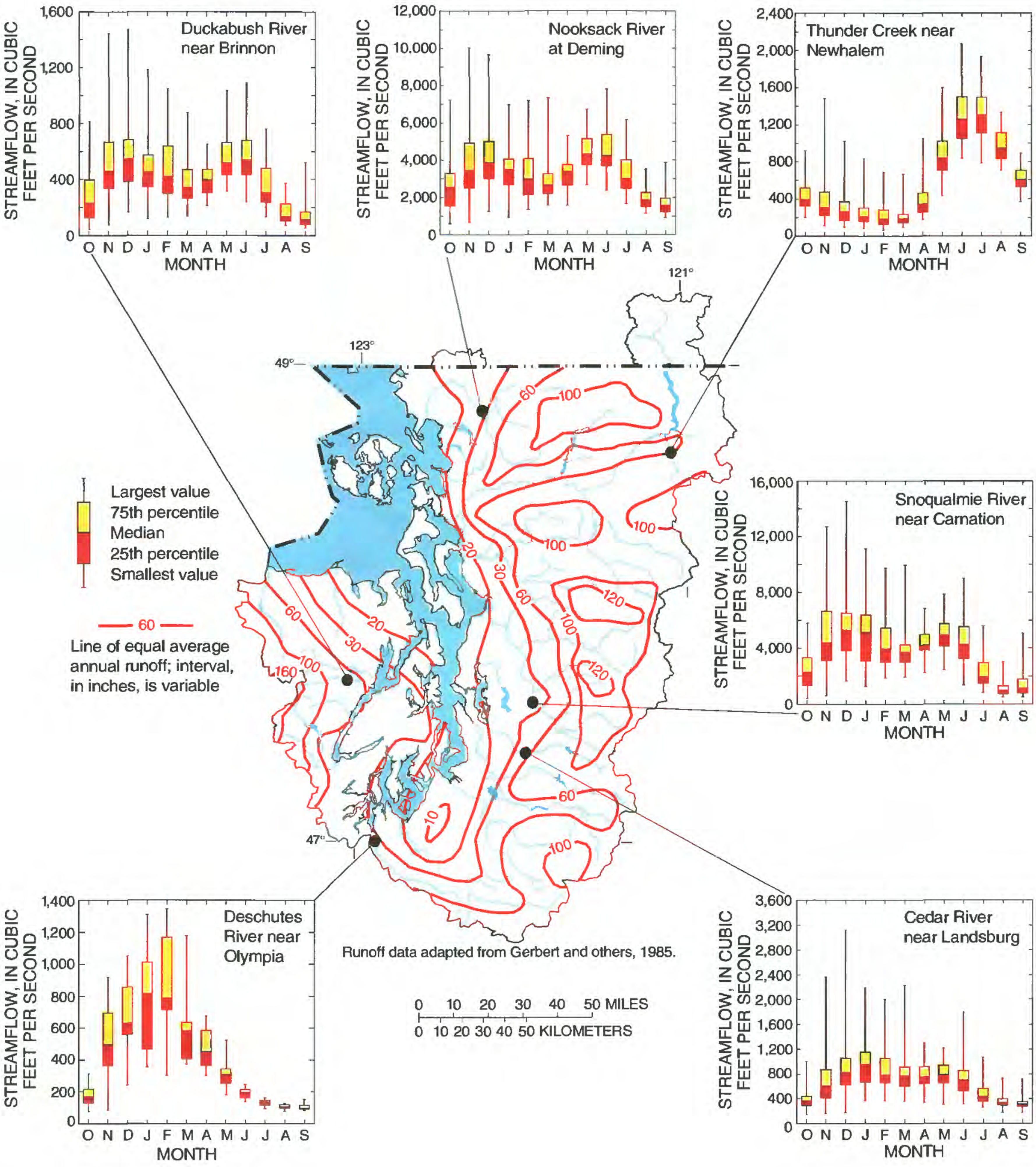


Figure 14. Monthly mean streamflows from selected streams and average annual runoff in the Puget Sound Basin. (Streamflow in cubic feet per second from Miles and others, 1993.)

Table 1.--*Mean annual streamflow of major Puget Sound Basin streams*

[Data modified from Miles and others, 1994, and Williams and others, 1985a and 1985b]

Gaging Station Name	USGS gaging station number	Drainage area (square miles)	Mean annual streamflow (cubic feet per second)	Mean annual runoff (inches)	Coefficient of variation of mean annual streamflow	Period of record (years)
Nooksack River at Ferndale	12213100	786	3,840	66.3	0.20	27
Samish River near Burlington	12201500	87.8	243	37.6	0.22	28
Skagit River near Mt. Vernon	12200500	3,093	16,600	72.8	0.19	53
North Fork Stilliguamish River near Arlington	12167000	262	1,890	98.1	0.21	65
Snohomish River near Monroe	12150800	1,537	9,540	84.3	0.21	30
Cedar River at Renton	12119000	184	666	49.2	0.25	48
Green River at Tukwila	12113350	440	1,490	46.0	0.23	27
Puyallup River at Puyallup	12101500	948	3,330	47.7	0.20	79
Nisqually River at McKenna	12089500	517	1,290	33.9	0.26	39
Deschutes River at Tumwater	12080010	162	330	27.7	0.34	6
Skokomish River near Potlatch	12061500	227	1,180	29.9	0.21	52
Dosewallips River near Brinnon	12053000	93.5	673	120.0	0.17	20
Dungeness River near Sequim	12048000	156	377	32.82	0.24	67
Elwha River near Port Angeles	12045500	269	1,500	75.7	0.21	83

Olympic Mountains. In contrast, the Deschutes River, typical of streams draining lowland areas, has little or no seasonal snowpack within its watershed and therefore has no increase in flow from mountain snowmelt in the late spring. In these lowland streams, monthly flows generally peak in January and February and trail off in the spring as precipitation decreases and water loss from evapotranspiration increases. Lowland streams typically have extended periods of low flow during summer.

High-altitude mountain streams draining glaciers or large snow fields show a different pattern as evidenced by Thunder Creek. These streams have lowest flows during the winter freeze and highest flows during the summer melt. Glacial runoff from high-altitude areas can contribute to sustained summer flows of some larger rivers as well. The Nooksack River drains the high altitude areas of Mt. Baker and Mt. Shuksan and has about 17 mi^2 of glaciers within its watershed. The Nooksack River has seasonal flows similar to those of the Snoqualmie River, but the flows are more sustained in July and August due to melting of snow and glacial ice from the higher altitudes.

The Cedar River is an example of a regulated stream. Variability of average monthly discharge in the Cedar River is less than in the adjacent Snoqualmie River and other unregulated mountain streams. Water from the Cedar River is put into reservoir storage during higher winter and spring flows and released during low summer flows.

Floods and Droughts

Seasonal high and low flows occur most years respectively during the winter rainy season and summer dry season, but extreme flows from major floods and extended droughts are much less frequent. Major floods in the Puget Sound Basin occur almost without exception during the winter months and most commonly during the months of November, December, and January. The floods generally result from intense, warm rains that originate from a southwesterly storm track, and the climatic conditions that cause this storm track may persist over an extended period causing multiple floods in a given year, such as occurred in 1989-1990 and 1995-1996.

These rains alone can cause flooding in the smaller lowland streams, particularly in urban areas that have a proportionately large (25 to 75 percent) amount of impervious area (King County Surface Water Management Division, 1987). In the larger river basins draining mountain areas, rainfall can be substantially augmented by melting snow, and the largest floods from these watersheds generally occur when the snowpack extends to the lower altitudes and is thin enough to be melted completely.

Flooding can be areally extensive, affecting many of the watersheds in the Puget Sound Basin during the same period. However, the magnitude of a flood can vary substantially from one watershed to another, depending on the storm track. For instance, during the flood of November 23 to 26, 1990, flooding of the greatest magnitude occurred in the central Puget Sound Basin, where flood peaks of a 100-year recurrence interval were measured in the Cedar and Snohomish River Basins. Flood peaks of a 10- to 75-year recurrence interval were measured in other rivers draining the northern Cascade Range, and flood peaks of 2- to 25-year recurrence intervals were measured in rivers draining the eastern Olympic Mountains (Hubbard, 1991 and 1994). Major recorded floods in the Puget Sound Basin are listed in table 2, including the river basin most affected and the range of recurrence intervals of the floods for streams within the river basin.

Although dry summers are the norm, extended droughts are not common in the Puget Sound Basin. Winter storms come ashore with sufficient regularity to provide a generally reliable source of winter precipitation. However, occasional abnormal warm ocean currents can affect the offshore high- and low-pressure regions diverting winter storms either north or south for extended periods causing a drought. Notable droughts, which resulted in periods of less-than-normal winter snowpack and streamflow in the Puget Sound Basin occurred in 1929-1931, 1939-1944, 1977, and 1985-1988 (Williams, 1989).

With this generally reliable supply of winter precipitation, annual streamflow in the Puget Sound Basin tends to be less variable than in many other parts of the western United States. The coefficient of variation of mean annual streamflow of streams in the Puget Sound Basin generally ranges between 0.20 and 0.35 (table 1), and this range is consistent for both large and small streams in both lowland and mountain watersheds. The ratio of the maximum annual mean streamflow to minimum annual mean streamflow, the measured extremes of annual streamflow, generally range between 2 to 1 and 3 to 1. For example, over the 65-year period of record, the 5,440 ft^3/s maximum annual mean streamflow of the Snoqualmie River near Carnation was only 2.35 times greater than the 2,310 ft^3/s minimum annual mean streamflow.

Table 2.--*Chronology of major floods in the Puget Sound Basin, 1815-1990*
[Data modified from Williams, 1989, Hubbard, 1991, and Hubbard, 1994]

Date	River basins most affected	Recurrence interval (years)
About 1815	Skagit River Basin	>100
November 1909	Snoqualmie River Basin	50 to 80
December 1933	Puget Sound Basin	10 to 60
January 1935	Skykomish River Basin	50 to 70
November 1949	Olympic Peninsula and Skagit River Basins	25 to 50
December 1964 and January 1965	Puyallup River Basin	30
January 1974	Nisqually River Basin	25
December 1980	Sauk and Skykomish River Basins	25 to 100
November 1989	Nooksack River Basin	10 to 50
January 1990	Deschutes and Puyallup River Basins	10 to 100
November 1990	Skagit River Basin	50
November 1990	Snoqualmie and Snohomish River Basins	50 to 100

Over a 10-year period, the year-to-year variations in streamflow tend to balance, resulting in even lower cumulative variability. The 10-year moving average of the annual mean streamflows for the three rivers shown in figure 15 indicates that over the period of record, the mean streamflow in any given decade has varied by no more than 38 percent from the mean streamflow in any other decade.

Stream Geomorphology and Aquatic Habitat

Streams are commonly grouped into three general geomorphic categories (low, mid, or high order) on the basis of their tributary network, and streams within each category tend to share common characteristics within a given region. Low-order streams are small headwater streams with few influent tributaries, mid-order streams drain larger watersheds and have a greater number of influent tributaries, and high-order streams are the largest rivers with the largest watersheds and extensive drainage networks.

Low-order streams in the Puget Sound Basin are found primarily within the Cascade Range and Olympic Mountains and secondarily within the Puget Sound Lowland. Low-order mountain streams represent greater than 70 percent of the cumulative channel length within the basin and are the initial conduits for water, sediment, and organic matter to the larger rivers that discharge to Puget Sound (Benda and others, 1992). These small streams, which typically drain steep forested mountain slopes, have high gradients (greater than 8 degrees) and are filled with colluvium that is characterized by coarse, unsorted sediments. In their natural state, these streams are subject to occasional landslides from bank failure or debris flows, and they contain substantial amounts of boulders and large organic matter (woody debris) that create well-developed pools and riffles. Their stream banks are well vegetated, their channels are well shaded, and they generally provide good habitat for salmon, trout, and other cold-water fish species.

Low-order streams within the lowlands generally originate in glacial drift on the upland plateau and in the foothills of the Cascade Range. Small lakes or wetlands often constitute the headwaters of these streams, and as they meander across the broad glacial drift plains and alluvial valleys, these streams are commonly associated with small streamside wetlands (King County Surface Water Management Division, 1987). Many of these lowland streams are low gradient and shallow and do not move as much sediment or organic material as do the headwater mountain streams. In their natural state, low-order lowland streams are in many ways similar to the low-order mountain streams in that they have dense riparian vegetation, well-shaded stream channels, an ample

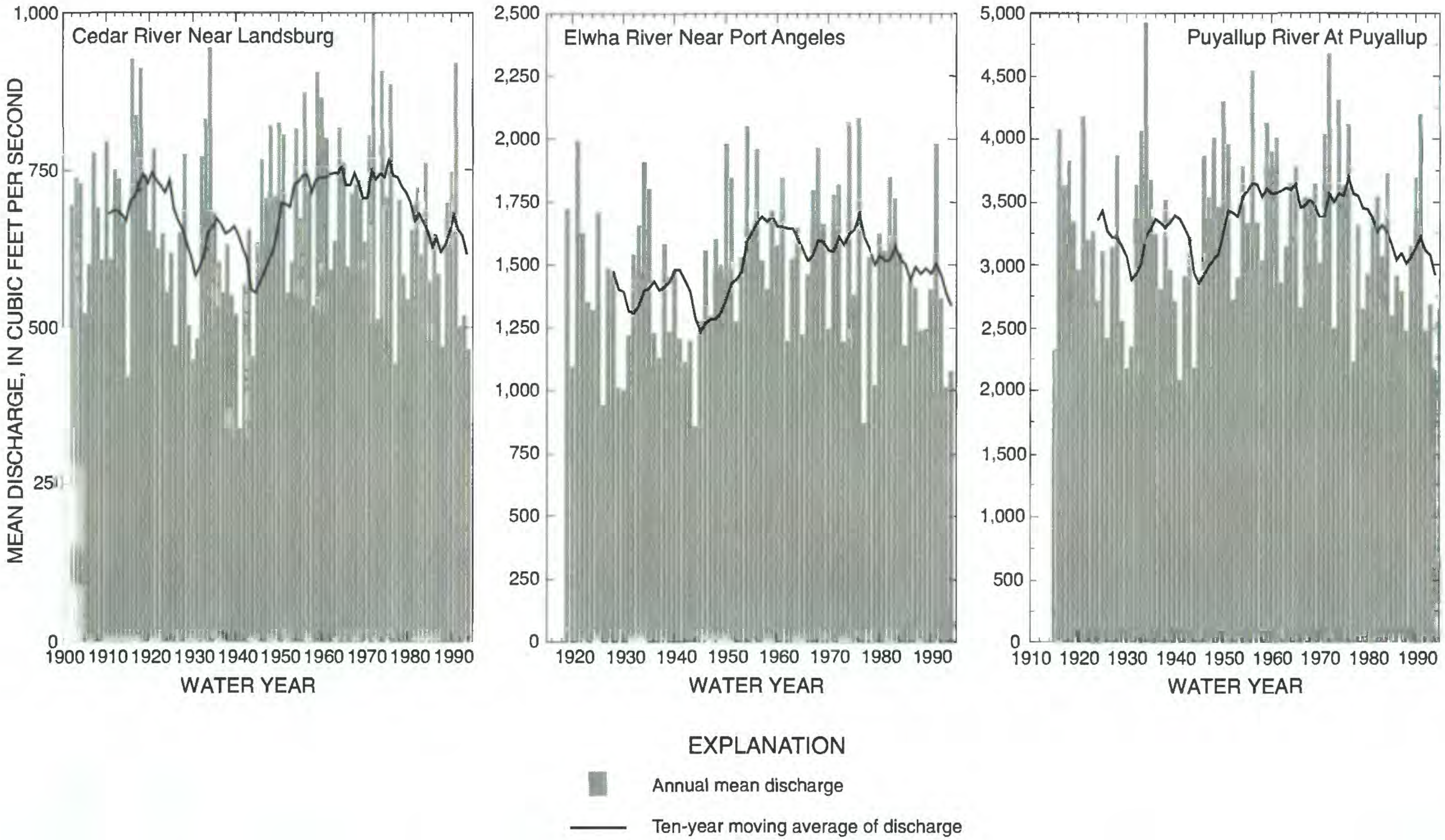


Figure 15. Ten-year moving average of annual mean discharges from selected rivers in the Puget Sound Basin.

supply of woody debris, and well-developed pools and riffles (Montgomery and others, 1995), providing good habitat for numerous fish species.

Mid-order streams within the Puget Sound Basin are found in the lower altitudes of the Cascade Range and Olympic Mountains and in the Puget Sound Lowland. These streams are characterized by moderate to steep gradients (1-6 degrees), substrates ranging from boulders to gravels, and in their natural state, abundant woody debris dams (Naiman and others, 1992). Mid-order mountain streams commonly occur along the floor of steep valleys and are fed by numerous small, low-order streams draining the mountain peaks or ridge tops. These mid-order mountain streams are subject to a variety of flow conditions, including large peak storm flows from winter rain on snow and low baseflows following the normally dry summer and fall. This hydrologic regime results in broad, meandering, boulder-strewn channels where the streams are not confined by bedrock or steep valley walls.

Mid-order lowland streams are fed by low-order headwater streams emanating from the upland plateau. As the mid-order streams traverse the edges of the upland plateau, they commonly cut long, deep ravines into the erodible glacial deposits. Within these ravines, the mid-order channels have a relatively high gradient (4-6 degrees) and are subject to periodic landslides, which contribute sediment and woody debris to the stream channel as in the low-order mountain streams. As these mid-order lowland streams emerge from the ravines, they enter a low-gradient outwash area prior to entering higher-order rivers or Puget Sound. In their natural state, the stream channels in this transition area contain large gravel beds, which are excellent lowland salmon and trout spawning habitat (King County Surface Water Management Division, 1987).

High-order streams or rivers within the drainage basin occur in the Puget Sound Lowland and are fed primarily by mid-order channels. Typically low gradients within these channels reduce their ability to transport large sediment. These channels are dominated by finer sediments such as gravel, sand, and silt. Large seasonal discharge and erodible banks result in rivers that, in their natural state, meander across broad floodplains that have seasonally flooded wetlands. In their lower reaches, these rivers discharge to Puget Sound through broad, flat deltas where the main channel breaks into sloughs or distributor channels that are surrounded by salt marshes. The heterogenous mixture of side channels and wetlands associated with these high-order streams are ideal spawning habitat and refuge for the developmental phases of many species of salmon (Scott and Crossman, 1985) and other aquatic organisms.

Prior to European settlement of the Puget Sound Basin, which began about 150 years ago, stream channels were relatively stable and provided plentiful habitat for salmonids and other cold-water fish species. In their natural state, the low- and mid-order streams provided ample shaded, cool water, clean spawning gravels, refuge pools formed from woody debris dams, and abundant food sources. The high-order streams and their associated side channels, wetlands, sloughs, and deltas provided migration corridors and development refuges for numerous species. However, timber harvesting and land development have had a profound effect on the physical characteristics of Puget Sound Basin streams and has resulted in a significant reduction in their habitat value.

Riparian vegetation has been widely removed from stream banks in urban, agricultural, and forested areas, and this has reduced the amount of woody debris available for recruitment to form dams and pools in stream channels. In a study of low-order streams draining forested areas of the Puget Sound Basin, the U.S. Forest Service (1993) reported that the number of pools has been reduced from a range of 25 to 60 pools per stream mile to only 5 to 25 pools per stream mile. In low- and mid-order lowland streams, the number of pools has been further reduced by removal of woody debris dams for flood control and fisheries management.

Clearcut logging and urbanization have also resulted in increased storm peak flows, stream-bank failures, and landslides in low- and mid-order streams. Spawning gravels have been scoured and stream channels have been armored with coarse substrate in high gradient stream reaches and buried by fine sediment transported to lower gradient reaches. In streams with greater than 15 percent of their bed composed of fine sediment, the emergence of developing coho salmon is significantly reduced. In a study within the Nooksack River Basin in 1983, 4 of 21 streams exceeded the 15 percent fine-sediment threshold (Lummi Tribal Fisheries Department, 1984).

High-order streams have been extensively channelized, and dikes have been built to control flooding of urban and agricultural lands. Surrounding side channels, wetlands, and salt marshes in the floodplains and deltas have been drained, diked, and filled for urban and agricultural land development, and fish passage to influent tributaries has been interrupted by dams, culverts, and other flood control structures. Physical alteration of high-order streams has been greatest in the urbanized central Puget Sound region, where salt marsh losses range up to 74 percent in the Snohomish River delta, 99 percent in the Duwamish River delta, and 100 percent in the Puyallup River delta (table 3).

Table 3.--Gain or loss of salt marshes in the major river deltas of the Puget Sound Basin [Data from Puget Sound Water Quality Authority, 1992]

River delta	Gain (+) or loss (-) (percent)
Lummi	-92
Nooksack	+9
Samish	-98
Skagit	-25
Stillaguamish	+20
Snohomish	-74
Duwamish	-99
Puyallup	-100
Nisqually	-28
Skokomish	-33
Dungeness	0

Combined, these physical changes have resulted in a significant decline in the available spawning and rearing habitat for salmon and other aquatic species. The habitat in as much as 1,200 miles of streams within the Nooksack Basin alone is estimated to be degraded and in need of restoration (Nooksack Salmon Enhancement Association, 1995). Habitat in the main stem of the Cedar River is estimated to have been reduced by approximately 56 percent (King County Surface Water Management Division, 1993). This level of degradation is probably typical of other Puget Sound Basin watersheds as well.

Aquatic Biota

The numerous cold-water rivers found throughout the Puget Sound Basin are home to an assemblage of migratory and resident fish typical of the Pacific Northwest. This assemblage is somewhat limited, compared with other parts of the country (Moyle and Herbold, 1987) and includes only 12 families of freshwater riverine fish represented by more than 35 species (Washington State Department of Fish and Wildlife and Bonneville Power Administration, 1992; Wydoski and Whitney, 1979; and J. Meyer, Olympic National Park, written commun., 1995). These families of fish include salmon and trout (Salmonidae), sturgeon (Acipenseridae), lamprey (Petromyzonidae), herring (Clupeidae), smelt (Osmeridae), sculpin (Cottidae), the minnow (Cyprinidae), mudminnow (Umbridae), catfish (Ictaluridae), sucker (Catostomidae), perch (Percidae) and Sunfish (Centrarchidae). The bull trout (*Salvelinus confluenthus*), green surgeon (*Acipenser medirostris*), Olympic mudminnow (*Novumbra hubbsi*), Pacific lamprey (*Lampetra tridentata*), and the river lamprey (*Lampetra ayresi*) are species found within the Puget Sound Basin that have been listed or are candidates for listing as threatened or endangered. All of the species within the herring family (shad), sunfish family (largemouth bass, smallmouth bass, bluegill, crappie, and pumpkinseed), catfish family (brown bullhead), and perch family (yellow perch) and two species in the salmon/trout family (eastern brook trout and brown trout) have been introduced to the area (Scott and Crossman, 1985). The abundance, distribution, and role of nongame fish in the structure and function of Puget Sound Basin streams and rivers is poorly understood except where the introduction of non-native fish species has contributed to the decline of native salmon (Bisson and others, 1992).

Most of the fisheries work within the Puget Sound Basin has focused on migratory (anadromous) salmon and trout. These fish species represent an important cultural, recreational, and economic component of the Pacific Northwest and the Puget Sound Basin. Anadromous salmon and trout are identified as unique stocks, which refer to "the fish spawning in a particular lake or stream(s) at a particular season, which fish to a substantial degree do not interbreed with any group spawning in a different place, or in the same place at a different season" (Washington State Department of Fish and Wildlife and others, 1993). Within the Puget Sound Basin, there are more than 200 identified stocks of anadromous salmon and trout including 29 chinook, 55 chum, 46 coho, 15 pink, and 4 sockeye salmon stocks and 60 steelhead trout stocks (Washington State Department of Fish and Wildlife and others, 1993). The Washington State Department of Fish and Wildlife and Western Washington Treaty Indian Tribes rated the status of each of these stocks and assigned each stock to one of four categories:

healthy, depressed, critical, or unknown. A healthy stock of fish is defined as experiencing production levels consistent with the available habitat and within the natural variations in survival for the stock. Depressed stock are those that are experiencing production levels below levels expected on the basis of available habitat and natural variations in survival rates, but are above the level at which permanent damage to the stock is likely. Critical stock are those that are experiencing production levels that are so low that permanent damage to the stock is likely or has already occurred. Unknown stocks are those for which insufficient information are available to rate the stock status. Of all of the anadromous salmon and trout stocks, the sockeye salmon has the poorest stock status (fig. 16). All of the sockeye salmon stocks within the Puget Sound Basin are either at depressed (75 percent) or critical (25 percent) population levels. The pink and chum salmon appear to be reasonably healthy, with 60 to 70 percent of the stocks characterized as healthy. For the chinook and coho salmon and steelhead trout, between 27 and 47 percent of the stocks are healthy, and between 25 and 34 percent of the stocks are depressed. The status of many of the stocks is unknown, particularly for steelhead trout, because of limited population data.

Several anthropogenic factors can be responsible for the decline of anadromous salmon and trout, and it is often difficult to determine the degree to which one specific factor is responsible for the decline in the fisheries (Bisson and others, 1992). However, it is generally accepted that the reduction in habitat complexity and quality is at least partly responsible for the decline in anadromous salmon and trout. The 1992 Washington State Salmon Stock Inventory report (Washington State Department of Fisheries and others, 1993) reviews the general condition of the habitat used by each stock and identifies specific environmental problems suspected to adversely affect stock survival. Figure 17 summarizes the percentage of times a number of anthropogenic and natural disturbances were cited as the potential cause for the decline in depressed or critical stocks of all salmon and trout species within the Puget Sound Basin. The diking and diversion of streams and rivers within agricultural areas was the most cited cause for aquatic habitat reduction for depressed stocks of salmon and trout. The increase in sediment loading from logging activities and the reduction in instream woody debris were also cited as factors contributing to the status of the depressed stocks. For the critical stocks, sedimentation resulting from logging activities was the most cited disturbance affecting these stocks.

Ecoregions

Ecoregions represent regions of relative homogeneity in ecological systems or in relations between organisms and their environments, and they are assigned on the basis of patterns of homogeneity of characteristics such as climate, soils and geology, vegetation and physiography (Omernik and Gallant, 1986; Omernik, 1987). Ecoregions provide a means by which environmental setting information of natural characteristics can be organized and presented in a clear and concise fashion. Once identified, ecoregions provide a framework for locating monitoring or reference sites and for extrapolating or regionalizing information from site specific studies (Omernik and Gallant, 1986).

Within the Puget Sound Basin, there are four ecoregions (fig. 18): the Coast Range (700 mi^2), the Puget Sound Lowland (6,362 mi^2), the North Cascade (5,498 mi^2) and the Cascade (1,172 mi^2). The Coast Range ecoregion encompases part of the Olympic Mountains and represents approximately 5 percent of the basin. This ecoregion is highly dissected by perennial streams with 2 to 3 miles of stream per square mile. Altitude ranges from sea level to 2,000 feet with peaks of 4,000 feet. Average annual rainfall ranges from 55 to 200 inches, most of which falls during the winter. Vegetation within the area is dominated by douglas fir, western hemlock, sitka spruce, and western red-cedar. The understory is composed of a continuous mat of shrub and herbaceous vegetation dominated by salmonberry, rhododendron, willow vine maple, and evergreen huckleberry (Omernik and Gallant, 1986; McNab and Avers, 1994). The streams within the region support anadromous salmon and trout as well as other cold water species of fish. Natural disturbances in the area are dominated by winter storms of 25-to-100 year recurrence intervals that produce windthrow and landslides.

The Puget Sound Lowland ecoregion is dominated by open hills and table lands of glacial and lacustrine deposits and represents 46 percent of the Puget Sound Basin. Altitudes within the region range from sea level up to 2,500 feet, and annual rainfall ranges from 15 to 50 inches. Stream density within the region is between 1 and 2 miles per square mile. The soils in the Puget Sound Lowland ecoregion were formed largely from glacial deposits and developed under the influence of coniferous forests. The forested areas in the region are dominated by Douglas fir, but also include lodgepole pine

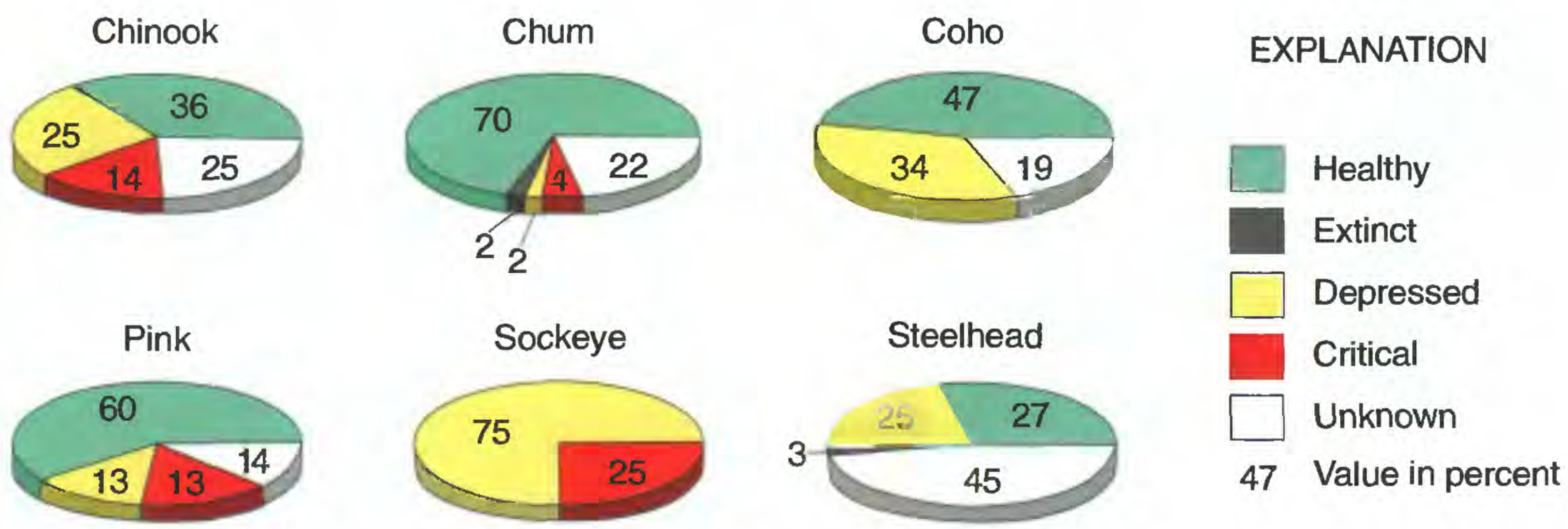


Figure 16. Salmon and steelhead stock status in the Puget Sound Basin. (Data from Washington State Department of Fisheries and others, 1993.)

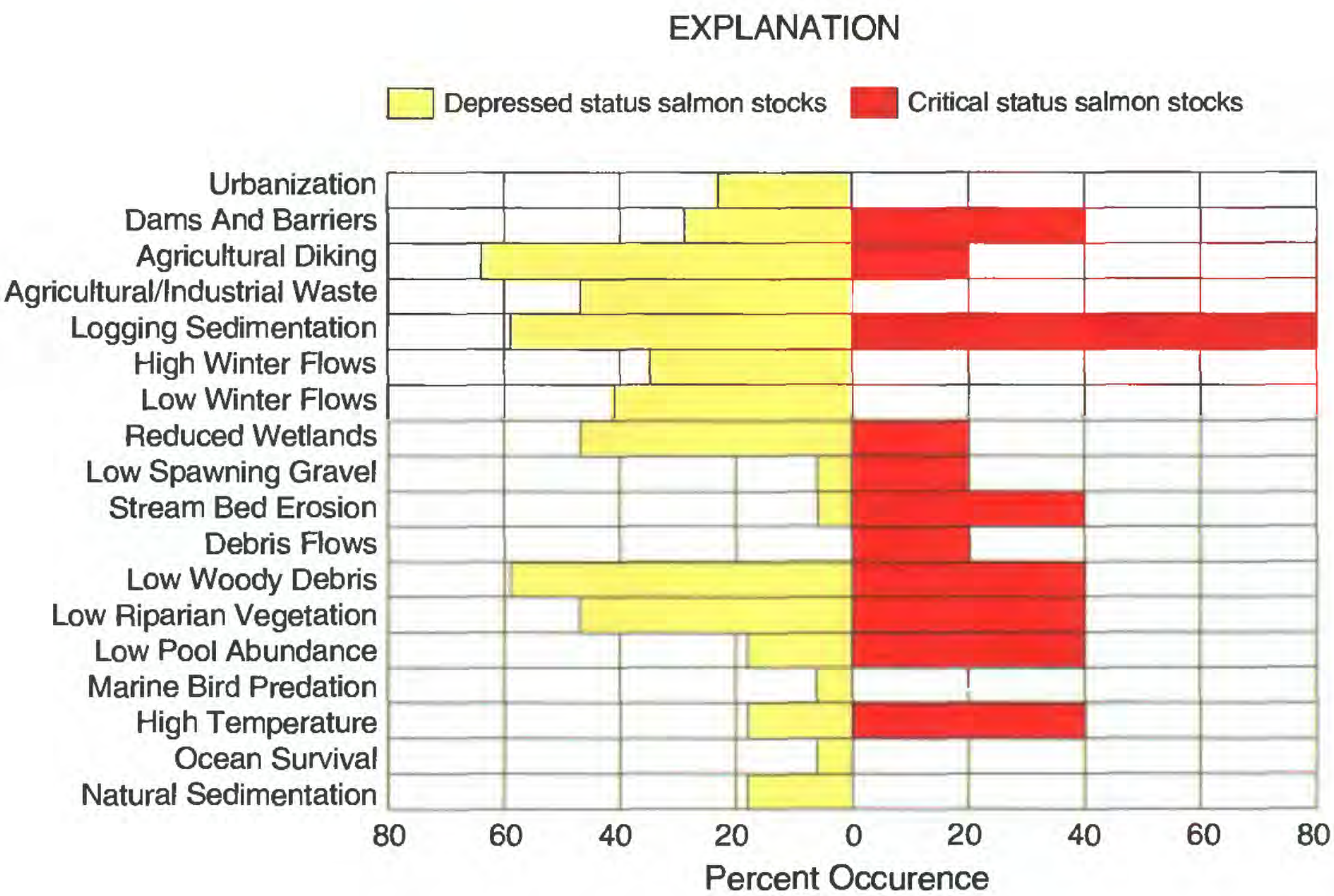


Figure 17. Percentage of times that each human or natural disturbance was cited as a potential cause of fish stock declines. (Data from Washington State Department of Fish and Wildlife and others, 1993.)

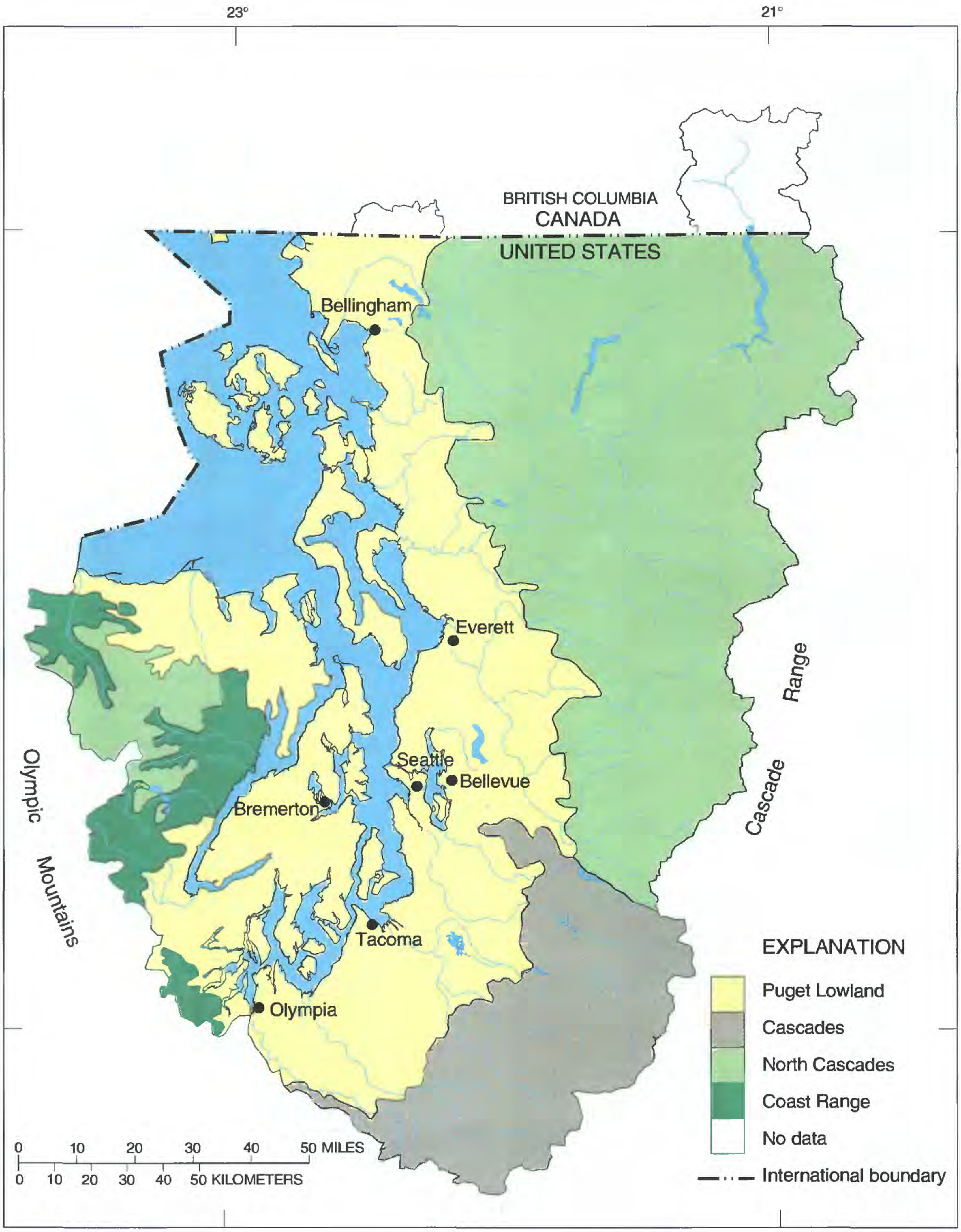


Figure 18. Ecoregions of the Puget Sound Basin. (Modified from Omemik and Gallant, 1986.)

and western white pine. The riparian zones have cottonwood, willow, ash, and alder (Omernik and Gallant, 1986; McNab and Avers, 1994). The streams in the Puget Sound Lowland ecoregion have numerous species of cold water fish such as salmon and trout.

The North Cascade ecoregion occupies 40 percent of the Puget Sound Basin. It is geologically dominated by igneous and metamorphic rock and some sedimentary rock. It is topographically irregular with peaks and valleys shaped by glacial activity. Altitude within the region ranges from near sea level to greater than 10,000 feet, and annual rainfall ranges between 50 and 120 inches. The stream density is between 1.5 and 2 miles of stream per square mile. The region is dominated by Douglas and silver fir with additional areas of western and Pacific silver fir, western white pine, western hemlock, and western red cedar. At higher altitudes, mountain hemlock, subalpine fir, whitebark pine, and Engelmann spruce can be found. Shrub cover is dominated by vine maple, rhododendron, huckleberry, blackberry, and Oregon grape (Omernik and Gallant, 1986; McNab and Avers, 1994). The limited alpine meadow areas are vegetated by bent grass, fescue, bluegrass, and sedges. The North Cascade ecoregion is a major timber harvesting area.

The Cascade ecoregion, to the south, represents 9 percent of the Puget Sound Basin. The vegetation in the Cascade ecoregion is similar to the North Cascade region. However, the two areas are different topographically and geologically. The Cascade ecoregion is dominated geologically more by volcanic activity than is the North Cascade. The Cascade topography is less rugged and is more plateau like with isolated peaks surrounded by larger alpine meadow areas. The streams in both areas are populated by resident and anadromous trout and salmon. The disturbance regime in both ecoregions is dominated by windthrow and the occasional fire (Omernik and Gallant, 1986; McNab and Avers, 1994).

Ground Water

The Puget Sound aquifer system, contained largely within the Puget Sound Lowland and the upper reaches of the alluvial valleys, is composed primarily of unconsolidated sediments that can be locally more than 3,000 feet thick. Coarse-grained outwash and alluvial deposits have significant water-bearing capacity and form the major aquifers in the Puget Sound Basin. Most domestic and large-capacity public supply wells are screened in these units. Fine-grained interglacial, lacustrine and till deposits are layered between the coarse-grained deposits and serve as confining and semiconfining units.

Successive glaciations resulted in highly variable sequences of deposits from one locality to another. This is illustrated in the stratigraphic columns for the southern Puget Sound Lowland, north-central Puget Sound Lowland, and the Fraser-Whatcom Basin shown in figure 19. To facilitate a regional assessment of ground-water resources and flow, Jones (in press) grouped local stratigraphic units into hydrogeologic units. Figure 20 shows the occurrence of these units in a cross section of an alluvial valley.

Hydrogeologic Units

Alluvial Aquifers: Extensive alluvial deposits are found in seven major river valleys and form separate aquifer units; these are the Nooksack, Skagit-Stillaguamish, Snoqualmie, Green, Puyallup, Skokomish, and Nisqually. The spatial distribution of these aquifers generally corresponds to the areas covered by alluvium shown in figure 3. Most of these alluvial aquifers are incised into glacial deposits, providing a path for water to flow from the unconsolidated glacial deposits into the alluvial aquifer and ultimately discharge to the river (flow path 1 in fig. 20). The lithology of this unit is generally coarse-grained; however, fine-grained deposits do occur, particularly in the lower valleys. The thickness of these deposits varies from a few tens of feet in the upper valleys to as much as 600 feet in the lower valleys. The hydraulic conductivities of fine-grained deposits range from 1 to 15 ft/d (feet per day). Coarse-grained alluvial deposits have hydraulic conductivities ranging from 100 to 700 ft/d, with an estimated average of approximately 200 ft/d (Vaccaro and others, in press).

Approximately 15 percent of the ground water used for the public drinking water supply is drawn from these aquifers. These units have high water tables (median depth to water is approximately 10 feet), suggesting that shallow ground water in those aquifers may be susceptible to contamination. Deeper ground water in these units may follow much longer flow paths and may thus be much less susceptible to contamination.

Semiconfining Unit: Outside of the alluvial valleys, this unit, where present, is the uppermost unit and consists of predominantly fine-grained till deposits; however, grain

Age kA[a]	Glaciation		Stratigraphy[d]	Corresponding Hydrogeologic Units: Whatcom Basin	North-central Puget Sound Lowland	Southern Puget Sound Lowland
	Interglacial		alluvium, marine deposits	Nooksack Alluvial aquifer	Skagit-Stillaguamish and Snoqualmie alluvial aquifers	Nisqually, Green, Puyallup, and Skokomish alluvial aquifers
10	Fraser Glaciation	Sumas Stade	Sumas Drift	Fraser aquifer	not present	not present
	Fraser Glaciation	Everson Interstade	Everson glaciomarine Drift	confining unit	surficial semi-confining unit	not present
	Fraser Glaciation	Vashon Stade	recessional outwash	confining unit	surficial semi-confining unit	surficial semi-confining unit
	Fraser Glaciation	Vashon Stade	Vashon till	confining unit	surficial semi-confining unit	surficial semi-confining unit
	Fraser Glaciation	Vashon Stade	advance outwash	Puget aquifer	Fraser aquifer	Fraser aquifer
	Fraser Glaciation	Evans Cr. Stade	Esperance Sand Member Evans Creek Drift Lawton Clay[e]	Puget aquifer	confining unit	Fraser aquifer
20	Olympia Interglacial		Quadra Formation Kitsap Formation	Puget aquifer	confining unit	confining unit
60	Possession Glaciation[b] Salmon Springs Glac.[c]		Possession Drift Salmon Springs Drift	Puget aquifer	Puget aquifer	Puget aquifer
80	Whidbey Interglacial[b] Puyallup Interglacial[c]		Whidbey Formation Puyallup Formation	Puget aquifer	Puget aquifer	Puget aquifer
>100	Double Bluff Glac.[b] Stuck Glaciation[c]		Double Bluff Drift Stuck Drift	Puget aquifer	Puget aquifer	Puget aquifer

a- kA denotes thousands of years before present.

b- As named in the Whatcom Basin and the north-central Puget Sound Lowland.

c- As named in the southern Puget Sound Lowland.

d- Formations may not be present throughout the basin. See Jones (in press) for details.

e- Lawton Clay forms part of the confining unit in the north-central portion of the Puget Sound Lowland.

Figure 19. Generalized stratigraphy and corresponding hydrogeologic units for the Puget Sound Basin. Adapted from Jones (in press).

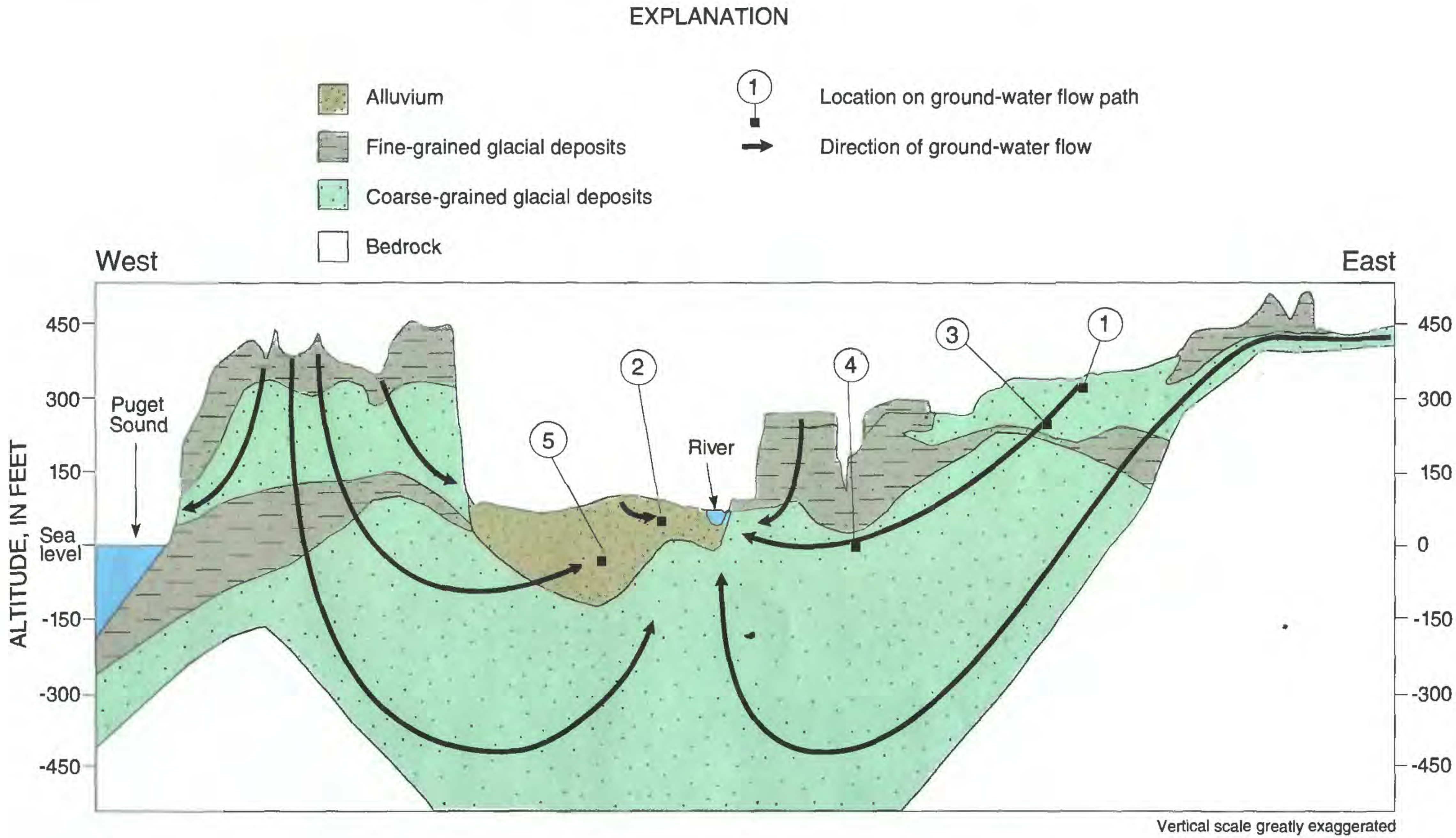


Figure 20. Generalized cross section and ground-water flow paths within an idealized alluvial valley in the Puget Sound Basin. Width of section is approximately 20 miles. For an explanation of locations on ground-water flow paths, see page 32.

sizes vary from clay to boulder. The Vashon till and other tills make up a large part of this unit, but lesser amounts of mudflow and glaciomarine deposits are also included. The semiconfining unit is classified as a distinct regional unit due to its effect on ground-water recharge (Vaccaro and others, in press), and it generally corresponds to the fine-grained glacial deposits at the surface shown in figure 3. The average thickness is between 20 and 40 feet, and hydraulic conductivity measurements of this unit ranged from 0.0002 to 53 ft/d with a median value of 0.12 ft/d (Vaccaro and others, in press).

In the past, this unit commonly has served as a drinking water supply for rural residents, with water being drawn from large diameter dug wells. Currently, wells tend to be completed in the underlying aquifers, which have higher yields and are less prone to contamination.

Fraser Aquifer: The Vashon advance outwash and proglacial deposits generally make up a large fraction of this unit; however, the Sumas Drift predominates in the Whatcom Basin. The Fraser aquifer generally represents the water-table aquifer except where alluvial aquifers are present. This aquifer is typically overlain by the semiconfining unit, but is exposed at the surface and unconfined in places. The unconfined portion of the Fraser aquifer generally corresponds with areas (fig. 3) that have coarse-grained glacial deposits at the surface. The average thickness of the Fraser aquifer is between 40 and 50 feet, and its hydraulic conductivities generally range from 10 to 100 ft/d.

This productive aquifer is the source of water for many public water systems and domestic users. Most ground water used for domestic water supply is withdrawn from this unit. Median depth to water in this unit is approximately 20 feet, and where this unit occurs at the surface, it is highly susceptible to contamination. .

Confining Unit: This areally extensive unit consists largely of interglacial deposits of lacustrine or fluvial origin. This unit includes the Olympia interglacial deposits in the southern Puget Sound Lowland, the Whidbey and Olympia interglacial deposits in the north-central Puget Sound Lowland, and the Everson glaciomarine deposits in the Whatcom Basin. The average thickness of the confining unit is between 20 and 65 feet, with estimated hydraulic conductivities ranging from 1E-05 to 1 ft/d. Lenses of coarse-grained deposits occur locally in this unit and function as aquifers. However, on a regional scale the low hydraulic conductivities found in the confining unit limit the flow of water from the Fraser aquifer to underlying units, which tends to protect the underlying Puget aquifer from contamination.

Puget Aquifer: The remaining undifferentiated glacial and interglacial deposits that exist below the base of the confining unit have been grouped into the Puget aquifer. The Puget aquifer generally occurs at approximately 250 feet or more below the land surface and can be as much as 1,000 feet thick (Jones, in press). Although insufficient data exist to distinguish discrete aquifer units on a regional scale, upper and lower Puget aquifer units have been classified in some regions on the basis of the identification of a clay confining unit of poorly known thickness and areal extent. The aquifer zones within this unit have hydraulic conductivities on the order of 40 ft/d. The Puget aquifer is a potentially significant drinking water source as wells are increasingly being installed in this unit.

Basement Confining Unit: This unit consists of consolidated rocks of a wide variety of types, including sandstone, chert, limestone, greenschist, basalt, gabbro and diorite. With a few exceptions (for example, the San Juan islands), outcrops of this unit occur largely in mountainous areas of little or no ground-water development (Molenaar and others, 1980).

Recharge

Net recharge is the amount of water per unit area that percolates through the unsaturated zone to the water table, resulting in an increase in ground-water supply. In addition to its effect on ground-water supply, net recharge may also affect ground-water quality as contaminants present at or near the surface may be transported down to the water table. Consequently, areas of high recharge are generally thought to be more susceptible to ground-water contamination than areas of low recharge. While net recharge largely depends on the quantity of precipitation in an area, several factors determine how much of this water reaches the water table, including (1) the hydrologic properties of the soil and geologic formations in the unsaturated zone, (2) topography, (3) evapotranspiration, and (4) anthropogenic features. The presence of soil and geologic formations with low hydraulic conductivities, steep topography, and impervious surfaces (parking lots, buildings, and roads) increase the likelihood that precipitation will become surface runoff and not recharge the aquifer. Evapotranspiration removes water directly from the surface or subsurface, also reducing recharge.

Because of the impact of recharge on both the quantity and quality of ground water, estimates of recharge on a regional scale are an important element in the study of ground-water resources. Models such as the Hydrologic Simulation Program-FORTRAN (HSPF) (U.S. Environmental Protection Agency, 1984), and the Deep Percolation Model (Bauer and Vaccaro, 1987) have been used by several investigators to provide recharge estimates for individual watersheds throughout the Puget Sound Basin (i.e., Dinicola, 1990; Bauer and Vaccaro, 1987). Vaccaro and others (in press) used model results for 26 of these individual basins to develop relations between precipitation and recharge for both till- and outwash-covered areas.

Recharge estimates for the Puget Sound area, corrected for land use effects (reduced recharge in urban areas), are shown on figure 21 (Vaccaro and others, in press). As expected, recharge estimates are larger in the upland river valleys, primarily due to higher precipitation, but coarse-grained surficial geology and less urban land use also favor recharge. Conversely, lowland areas receive less precipitation and thus receive less recharge. Urban areas, such as Tacoma and Seattle, have the lowest recharge estimates because of large impervious areas that reduce infiltration.

Ground-Water Flow

An understanding of the ground-water flow system is an important element in the evaluation of both water quantity and quality issues. For example, knowledge of ground-water flow directions allows for the delineation of areas that are vulnerable to the spread of contaminants from actual or potential sources.

Ground-water levels are largely controlled by topography, resulting in ground water locally flowing toward areas with lower altitudes (Vaccaro and others, in press). Water levels for shallow wells (less than 105 feet deep) provide a reasonable estimate of water table conditions and were found to be the most strongly correlated with land surface altitude ($r^2 = 0.99$), with ground water flowing toward the river valleys or directly to Puget Sound. Water levels in deeper wells (greater than 105 feet deep), likely screened in the lower-Fraser and-or the upper-Puget aquifers, were also strongly correlated with land surface altitude ($r^2 = 0.87$). Ground-water-level contours and flow directions were determined using both water-level measurements and estimates based on land surface altitude (fig. 22). Ground-water flow is generally toward the river valleys or Puget Sound, with little or no flow between river valley basins. On the basis of water level estimates for both shallow and deeper waters, there does not appear to be a single regional ground-water flow system in the Puget Sound Basin, but rather there are discrete local flow systems within each river valley that are not hydraulically connected to each other.

The water-level map shown in figure 22 demonstrates the importance of topography and the major discharge features to ground-water flow. To better illustrate how these factors contribute to the formation of isolated flow systems, cross-sectional ground-water flow paths for an idealized alluvial valley are shown in figure 20. Topographic control is indicated just west of the alluvial valley, where steep terrain coincides with steep lateral hydraulic gradients. Conversely, hydraulic gradients are much shallower in the eastern part of the section, which has a gentler slope. In both cases, water flows toward the alluvial valley, with many flow paths that pass through both the Fraser and Puget aquifers before reaching the alluvial aquifer. Upward gradients are observed below the river, as ground water in the alluvial aquifer discharges to the river. Similarly, the effect of ground-water discharge to salt water on flow is indicated in the western part of figure 20, where steep hydraulic gradients occur between a topographic high and the Puget Sound. Lastly, because the basement confining unit (BCU) is much less permeable than the unconsolidated sediments, flow is essentially restricted to the unconsolidated sediments. This results in shorter ground-water flow paths than would be possible if flow was not partially controlled by the geometry of the top of the BCU (fig. 20). The combination of all of the above factors--topographic control, the presence of river valleys and saltwater bodies, and the BCU--contribute to form an aquifer system that is characterized by short flow paths and many isolated flow systems discharging to the Puget Sound or its tributaries.

Surface Water-Ground Water Interactions

Stream-Aquifer Interactions: As discussed in the previous section, the major rivers constitute local topographic lows that exert a significant influence on the flow of ground water in the Puget Sound region. The flow paths in figure 20 illustrate the hydraulic connection between ground water and surface water, indicating that ground-water discharge to streams (baseflow) may significantly contribute to streamflow. In fact, excepting areas where ground water discharges directly to salt water (the coastal and island regions), model calculations for several small stream basins in the Puget Sound Lowland indicate that in most cases more than 70 percent of ground-water recharge eventually discharges to streams as baseflow,

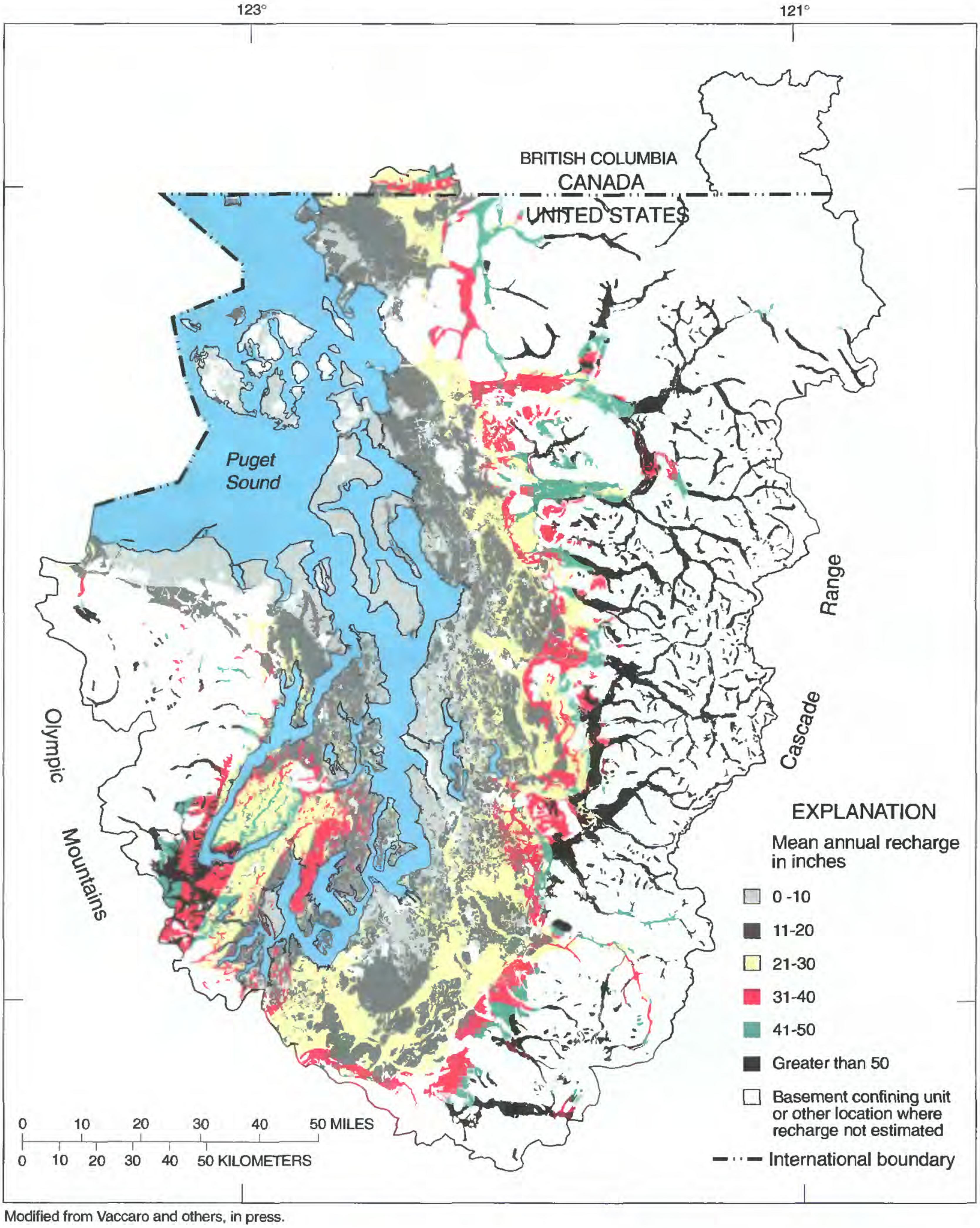


Figure 21. Estimated distribution of mean annual ground-water recharge for the Puget Sound aquifer system. (From Vaccaro and others, in press)

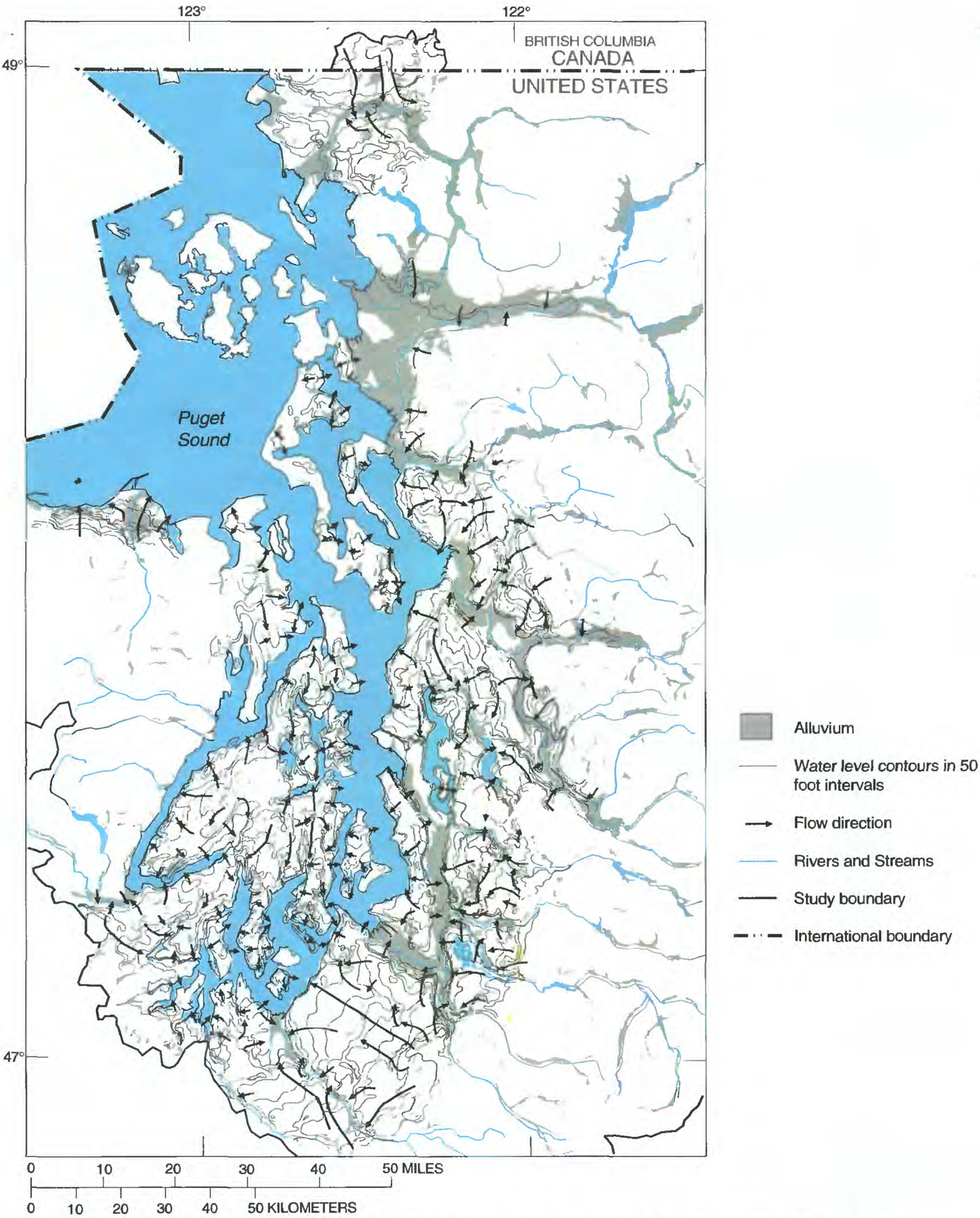


Figure 22. Ground-water level contours and flow directions showing localized flow systems in the Puget Sound aquifer system. (From Vaccaro and others, in press)

usually contributing more than 50 percent of streamflow (Vaccaro and others, in press). On a larger scale, streamflow data for the Nooksack River showed that it gained flow along its entire length, with approximately 80 percent of recharge in this basin ultimately discharged to the river. Similarly, the Snoqualmie River also appeared to gain water along almost its entire length (Turney and others, 1995). In the Soos Creek watershed, Culhane and others (1995) suggest that ground-water withdrawals have caused significant reductions in streamflow during low flow periods. The above evidence suggests that stream-aquifer interactions have a major influence on both ground-water flow directions and the quantity and quality of streamflow throughout the region.

Salt Water-Aquifer Interactions: Saltwater bodies receive much of the ground-water discharge from islands and other coastal areas that are in close proximity to Puget Sound. Ground-water flow directions shown in figure 22 and the flow paths in the western most part of figure 20 illustrate this ground-water discharge mechanism. Estimates of direct ground-water discharges to salt water for sections on Bainbridge, Whidbey, and Camano islands vary from 30 to 80 percent of total discharge (Vaccaro and others, in press). Ground-water discharge from islands and coastal areas makes up to 5 percent of the freshwater discharge to the Puget Sound (Vaccaro and others, in press).

Although under natural conditions freshwater discharges to salt water, ground-water pumping in coastal areas may decrease freshwater hydraulic heads enough to cause the flow direction to reverse (Jones, 1985, and Sapik and others, 1989). This results in the intrusion of salt water into freshwater aquifers and undesirable increases in dissolved ion concentrations (Walters, 1971). Large concentrations of chloride, indicative of saltwater intrusion, have been observed in wells near the coastline, particularly in San Juan and Island Counties (Whiteman and others, 1983; Dion and Sumioka, 1984; and Turney, 1986).

Aquifer Susceptibility

Aquifer susceptibility is defined as the relative ease with which a contaminant applied at or near a land surface can migrate to an aquifer (same as the definition for aquifer sensitivity from the U.S. Environmental Protection Agency, 1993). Identification of areas where aquifers are more susceptible to contamination is an important tool for land use planners; potential sources of contamination can be more closely monitored or not sited in these areas.

Aquifer susceptibility is based largely on the travel time required for ground water to reach a given part of an aquifer. Aquifers or parts of aquifers with shorter travel times are considered more susceptible. As such, aquifer susceptibility is based on the intrinsic characteristics of the saturated and unsaturated zones such as (1) depth to water, (2) surficial geology, and (3) the ground-water flow system, including aquifer recharge and discharge conditions.

Depth to Water: The water table is generally shallow in the Puget Sound Basin. The average depth to water for more than 1,500 wells in the USGS data base is less than 25 feet. In the alluvial aquifers, the water table is often within 10 feet of the surface. As such, travel times to reach the water table in this region are typically short.

Surficial Geology: The most significant geologic feature limiting the migration of contaminants to the water table is the presence of the semiconfining unit. The low hydraulic conductivity of this unit reduces the amount of recharge (and contaminants) that can reach the water table. Conversely, in areas where the Fraser aquifer is unconfined, recharge to the aquifer is relatively unimpeded.

Ground-Water Flow System: The flow paths shown in figure 20 are generally representative of the Puget Sound aquifer system. Ground-water flow is locally controlled by ground-water discharge to surface water. The Fraser aquifer (Point 3 in fig. 20) and very shallow parts of the alluvial aquifer (Point 2) are more likely to receive recently recharged ground water than is the Puget aquifer (Point 4) and deeper parts of the alluvial aquifer (Point 5). Under certain circumstances, the Fraser and alluvial aquifers can be quite susceptible to contamination. Where the Fraser aquifer is not overlain by the semiconfining unit, contaminants, if present at the surface, can easily reach the shallow water table. The shallow part of alluvial aquifers may also be susceptible, to the extent that they are part of a local flow system. However, the Puget and deeper parts of the alluvial aquifers are less susceptible to contamination because they receive waters by longer flow paths.

Water Use

Excluding water used for hydroelectric power, total freshwater use in the Puget Sound Basin (table 4) for 1990 was approximately 819 million gallons per day. The primary uses of fresh water were domestic water supply (49.5 percent), industrial (21.2 percent), irrigation (17.7 percent), and commercial (11.6 percent). Approximately

Table 4.--*Estimates of annual water use in the Puget Sound Basin in million gallons per day for 1990*
[by type, in million gallons per day; NA denotes that data is not available; < denotes less than]

Type of water use	Self-supplied ground water	Self-supplied surface water	Supplied by public system	Total
Commercial	17	<1	78	95
Domestic	58	0	347	405
Industrial	58	51	65	174
Irrigation	NA	NA	NA	145

80 percent of the water used for domestic, industrial, and commercial water uses was consumed in King, Pierce, and Snohomish Counties, the most populous counties. Irrigation water use was highest in Whatcom County, which has the most agricultural land use. The second highest use of irrigation water was in Clallam County, which receives the least amount of rainfall in the study area (fig. 9). More than half of the water used for irrigation in the Puget Sound Basin was applied in Whatcom and Clallam Counties on approximately 34,000 and 15,000 acres of agricultural land, respectively.

Both surface and ground water are important sources of water in the basin. Surface water supplies approximately 60 percent of the water used and provides most of the drinking water for the major urban centers. The cities of Seattle, Tacoma, Bellevue, Everett, Bellingham, and Bremerton receive most of their water from reservoirs or surface-water diversions located in mountain or upland areas. Both ground and surface waters are used for irrigation in roughly equal quantities. Ground water is the major source of drinking water in most rural areas, in part because it is more easily self supplied. Ground water is also used as the sole or principal source of drinking water in some areas because it is the only drinking water source that is physically, legally, or, economically available. The U.S. Environmental Protection Agency (EPA) defines the ground-water supply for these areas as sole or principal source aquifers if the aquifer supplies at least 50 percent of the drinking water consumed in the area. The EPA has designated seven local sole source aquifers in the Puget Sound Basin. The location of these sole-source aquifers and the distribution of public water supply wells in the basin are shown in figure 23.

Population

More than 3.6 million people reside in the Puget Sound Basin, 98 percent of whom live within 20 miles of the Puget Sound shoreline (fig. 24). The city of Seattle, home to more than 500,000 people, is the largest city in Washington State. Seattle is at the center of an urban corridor that includes western Snohomish, King, and Pierce Counties, eastern Kitsap County, and the cities of Tacoma, Bellevue, and Everett. These four central Puget Sound counties account for 88 percent of the basin's total population. Population density in these and other counties is greatest in the established cities and towns along the shores of Puget Sound. Population density gradually decreases inland in the suburban areas surrounding the major urban centers, and in the predominantly agricultural alluvial valleys. The foothills and mountains, which constitute over one-half of the Puget Sound Basin, are virtually uninhabited.

The region's population has grown at a steady pace for the last several decades and increased by 37 percent, or nearly 1 million people, between 1970 and 1990. Although the rate of population growth is expected to slow somewhat over the next decade, the region still faces a forecasted gain of another 1.1 million people by the year 2010 (Puget Sound Water Quality Authority, 1988). Nine of the 10 fastest growing counties in Washington State between 1980 and 1990 are located in the Puget Sound Basin, with Island (54 percent), San Juan (54 percent), Snohomish (53 percent), and Jefferson (52 percent) counties topping the list (Washington Office of Financial

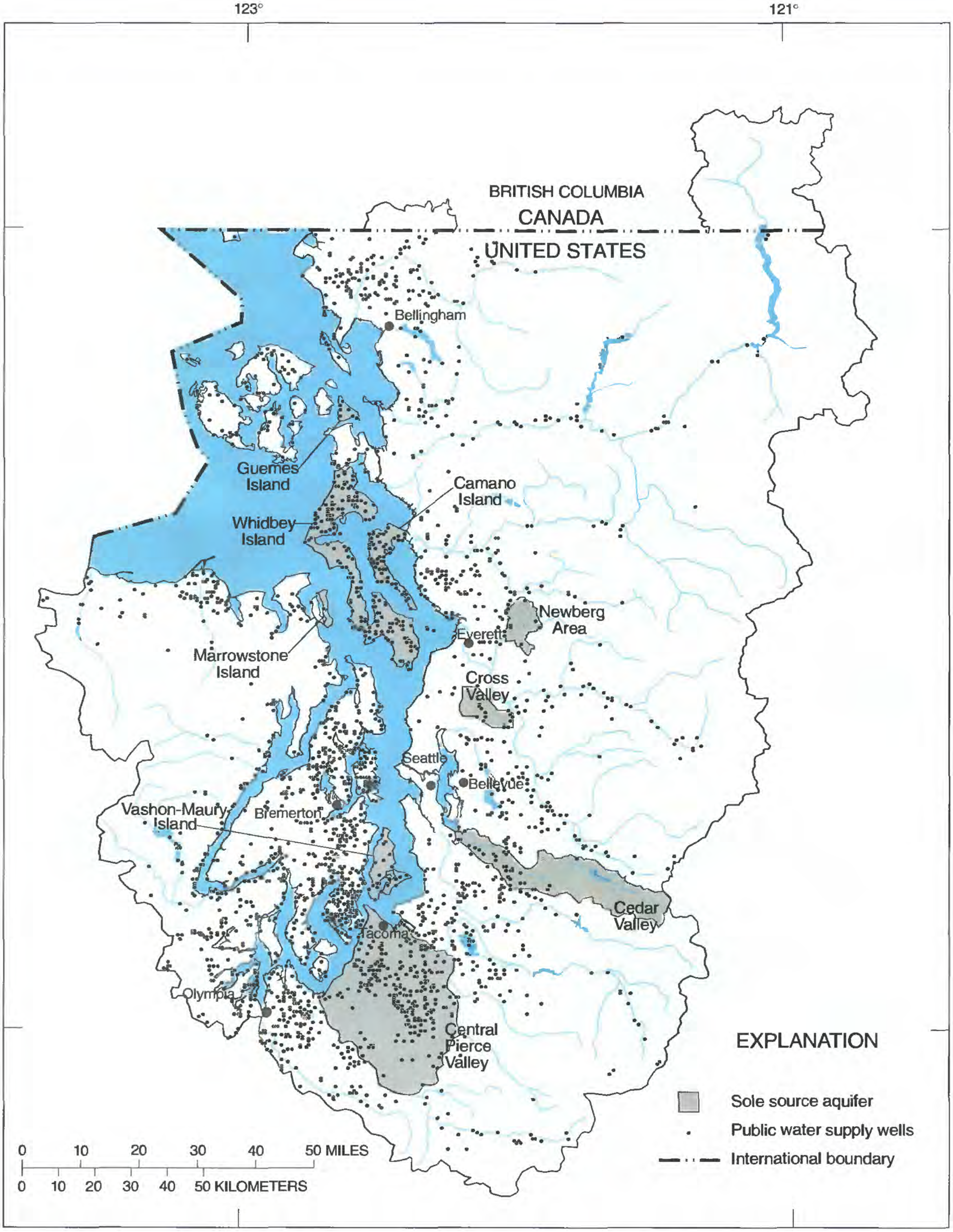
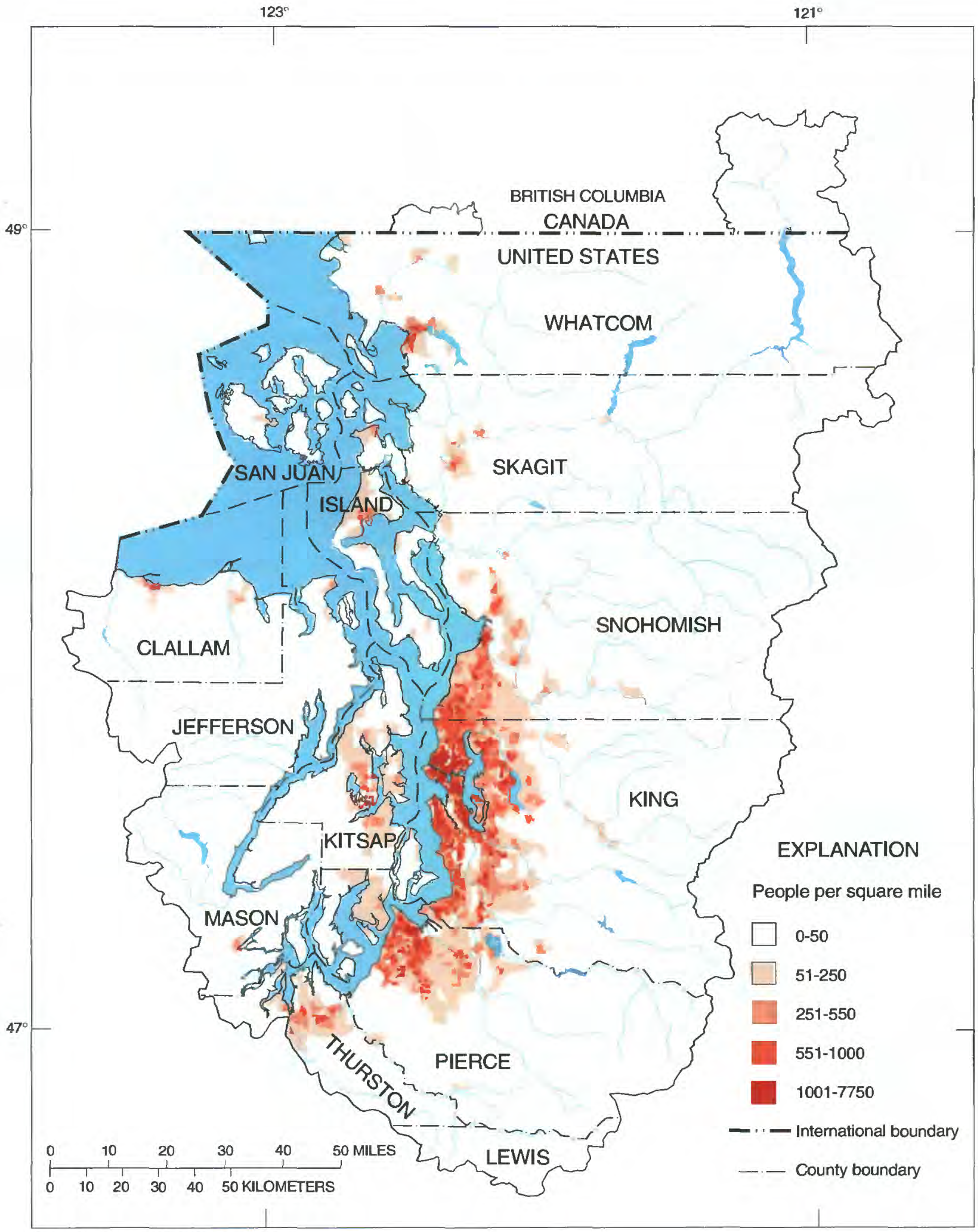


Figure 23. Locations of designated and proposed sole source aquifers and distribution of public supply wells in the Puget Sound Basin. (Sole-source aquifers from the U.S. Environmental Protection Agency, 1996. Well locations from Ginny Stern, Washington State Department of Health, written communication, 1996.)



Data from Bureau of the Census, 1990.

Figure 24. Population density in the Puget Sound Basin.

Management, 1995). Figure 25 shows that the highest growth rates on a percentage basis in the Puget Sound Basin are found primarily in small, rural counties where total population is low. Population growth in gross numbers is much greater in the four-county central Puget Sound region, which gained 738,000 people since 1980 (fig. 26). King County alone is home to approximately 1.6 million people, and accounted for more than one third of the basin's total population growth since 1980.

Land Use

Land-use information is helpful in interpreting water-quality data. How land is used and how the associated waste by-products are managed largely define the type, location, and amount of contaminants that are found in surface and ground water. There has been no comprehensive land-use survey done in the Puget Sound Basin since the Puget Sound Task Force survey in 1970 (Pacific Northwest River Basins Commission, 1970c) and the USGS national land-use surveys of the mid-1970's (Fegeas and others, 1983). Most land-use information described below is derived from the Puget Sound Task Force survey, which has been updated with more recent information where it is available. Although much of this information is now over 20 years old, it represents a general land-use pattern that is still relevant today.

Forest, urban, and agriculture are the three principal land uses in the Puget Sound Basin. In 1970 forest covered approximately 6.8 million acres, or 78 percent of the basin (fig. 27). Urban areas covered approximately 8 percent of the basin and were concentrated along the shores of Puget Sound. Agriculture covered close to 6 percent of the basin and was confined to the lowlands, mostly along the lower reaches of the alluvial river valleys. The remaining land in the Puget Sound Basin was made up of high-elevation tundra (2.7 percent), rangeland (2.4 percent), perennial snow (1.8 percent), wetlands (0.8 percent), and barren lands (0.4 percent). Today (1996), urban land use may have increased to cover as much as 11 percent of the basin, and forest land may have decreased to cover only 75 percent of the basin.

Each of the major drainages to Puget Sound has more than one-half of its watershed occupied by forest land. Forest-land cover ranges between 56 percent of the Cedar/Lake Washington Basin to 94 percent of the Skokomish River Basin (table 5). Urban land use varies between basins and is concentrated in the small drainages along the shores of Puget Sound (27 percent) and the Strait of Georgia (13 percent) and in the Cedar/Lake Washington (42 percent) and Green River/Duwamish Waterway (20 percent) Basins, which drain a large part of the Seattle metro area. Most major drainages also have some agricultural land use areas within their watersheds with the largest percentages ranging between 15 and 24 percent in the Nooksack River Basin, the Strait of Georgia drainages, and the San Juan Islands, all in the north Puget Sound Basin.

<u>Urban</u>

Urban land use includes residential, commercial, and industrial areas, as well as cemeteries, airports, roadways, and railroads. Urban development in the Puget Sound Basin has occurred along the shores of Puget Sound and is concentrated in seven major cities: Seattle, Tacoma, Bellevue, Bremerton, Everett, Olympia, and Bellingham (fig. 1 and fig. 27). Heavy industry is generally located on the shores of the urban bays and along the lower reaches of their influent tributaries, such as Commencement Bay and the Puyallup River in Tacoma and Elliott Bay and the Duwamish Waterway in Seattle (fig. 1 and fig. 6). High-density commercial and residential development occurs primarily within and adjacent to the major cities. Development in recent years has continued around the periphery of these urban areas (fig. 28), but has trended toward lower density. The population density of developed land in King County decreased from an average of 8.2 persons per acre before 1960 to 4.4 persons per acre after 1960 (Puget Sound Water Quality Authority, 1988). Between 1970 and 1990, the population in the central Puget Sound region increased by 38 percent, but land consumed by new development rose 87 percent (Puget Sound Water Quality Authority, 1992). This trend has resulted in increasing suburban sprawl and a generally north, south, and eastward migration of developed land in the central Puget Sound Basin. If current development patterns persist, by the year 2000 almost 1.3 million acres, or 15 percent of the land in the Puget Sound Basin will be in urban and residential uses (Puget Sound Water Quality Authority, 1988). Much of this growth is expected to occur along the fringe of existing urban centers and is projected to result in a 7 percent decrease in forest lands. Employment is expected to shift increasingly toward services, government, trade, and construction, creating a continued demand for residential, commercial, office, and retail land uses.

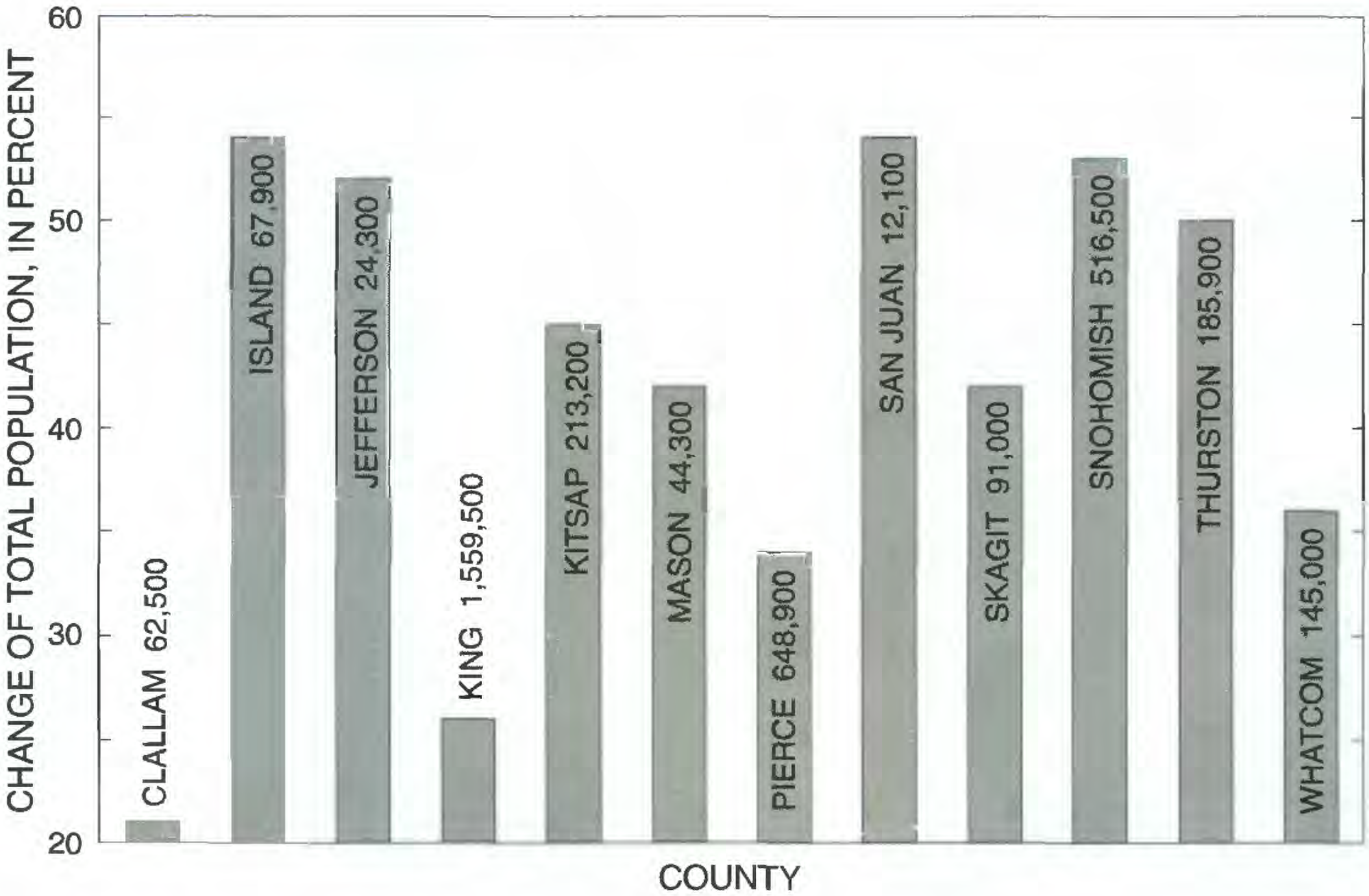


Figure 25. Population growth rates from 1980-1994 in twelve counties in the Puget Sound Basin. (Adapted from Puget Sound Water Quality Authority, 1992 and Washington Office of Financial Management, 1995.) Values indicate 1994 population.

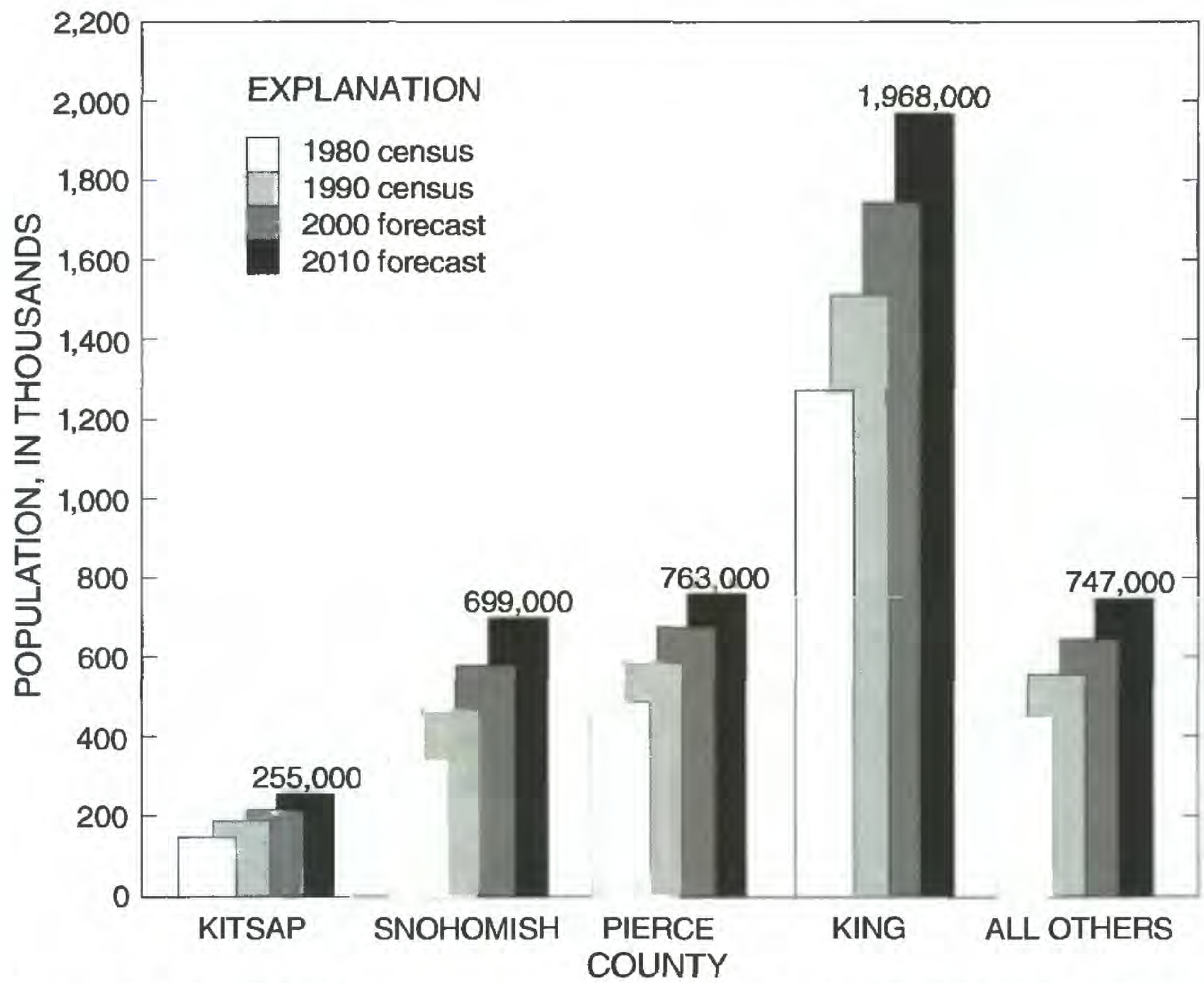
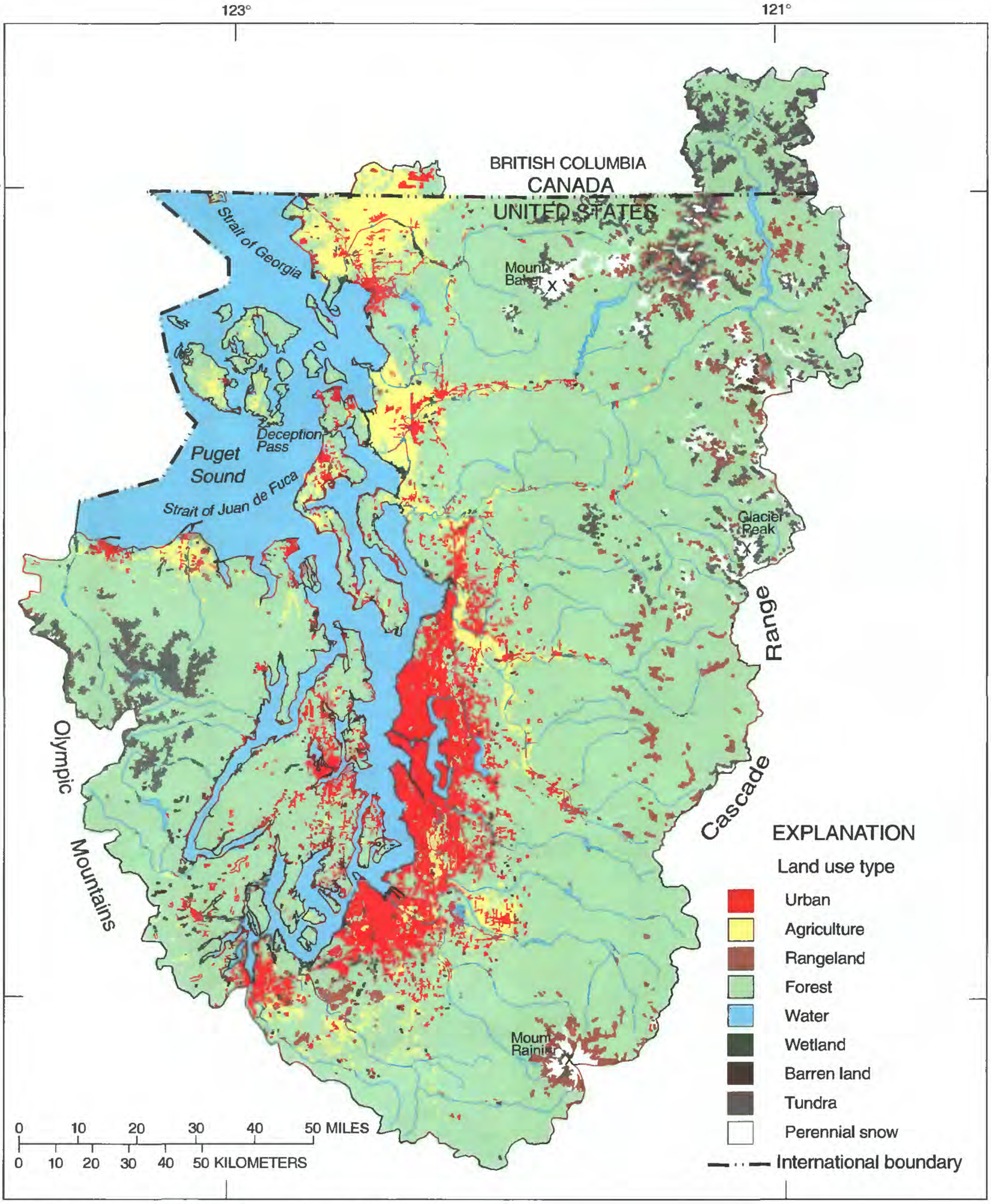


Figure 26. Current and projected population of selected counties in the Puget Sound Basin. (Adapted from Puget Sound Water Quality Authority, 1992 and Washington Office of Financial Management, 1995.)



Land use digital data modified from Fegeas and others, 1983.

Figure 27. Generalized land use in the Puget Sound Basin.

Table 5.--Land use and land cover in Puget Sound Basin watersheds
[Landuse/landcover reported in percent; other category includes wetlands, perrenial snow, range land, and barren land]

		Land Use (percent)		
Watershed	Forest	Urban	Agriculture	Other
Strait of Georgia Drainages	60	13	24	4
San Juan Islands	74	4	15	7
Nooksack River	73	3	15	9
Skagit River	80	1	3	17
Stillaguamish River	89	3	5	3
Snohomish River	86	5	5	4
Cedar River/Lake Washington	56	42	1	1
Green River/Duwamish Waterway	72	20	7	1
Puyallup River	82	7	4	8
Nisqually River	86	2	6	6
Deschutes River	84	6	8	3
Skokomish River	94	0	1	5
Hood Canal Drainages	87	4	0	9
Puget Sound Drainages	62	27	6	5
Strait of Juan De Fuca Drainages	78	3	5	14

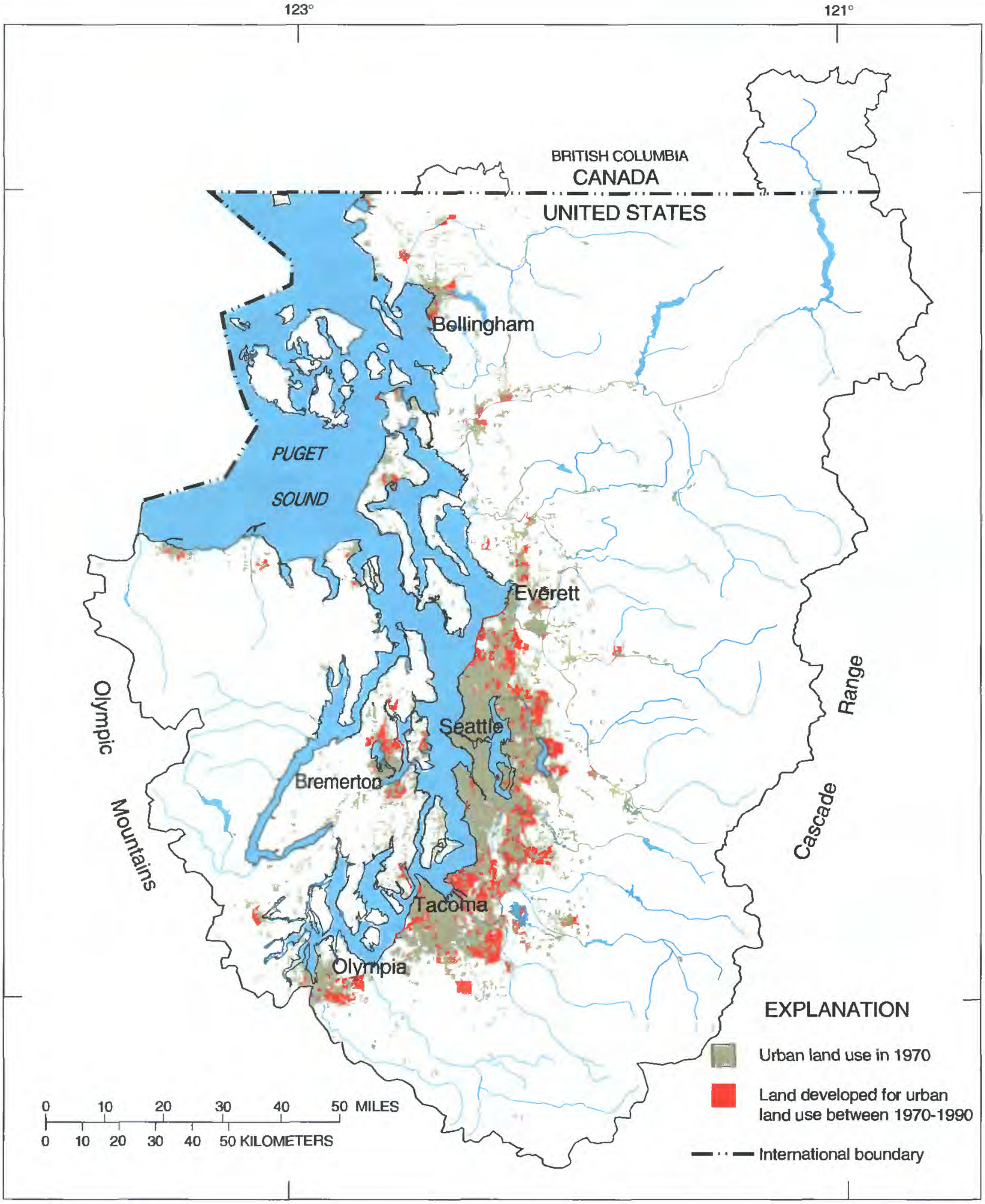


Figure 28.--Increase in area of urban land use from 1970 to 1990. (Area of land use modified from Fegeas and others, 1983. Increase in urban land use calculated only for the United States using 1990 census data (Bureau of the Census, 1990, 1991a, 1991b, 1991c, 1991d) following the method of Hitt, 1995).

Because most urban development has occurred along the shores of Puget Sound and in the lower reaches of its major tributaries, most waste discharges also occur in these areas. Of the 28 major municipal wastewater discharges (1 million gallons per day or more), 22 discharge directly to Puget Sound, 2 discharge to tidally influenced river reaches, and 4 discharge to freshwater river reaches (fig. 29) (Puget Sound Water-Quality Authority, 1988). Municipal discharges to Puget Sound require secondary treatment, and about three-fourths of the treatment plants have been upgraded to this level (Puget Sound Water Quality Authority, 1992). Of the 23 major industrial waste-water discharges (scoring 80 points or more on the EPA NPDES scale), 12 discharge directly to Puget Sound, 7 discharge to tidally influenced river reaches, and 4 discharge to freshwater river reaches (Puget Sound Water Quality Authority, 1988). Together, municipal and industrial facilities discharge approximately 900 million gallons of wastewater per day to Puget Sound. Point-source discharges from combined storm and sewage overflows (CSOs) also occur during periods of heavy rain. One-hundred and forty-one CSOs discharge approximately 2.8 billion gallons per year to Puget Sound and its tributaries. The Seattle metro area alone has 91 CSOs that discharge more than 2 billion gallons per year (Puget Sound Water-Quality Authority, 1992).

Hazardous waste sites and hazardous waste releases are also concentrated in the urban areas along the shores of Puget Sound. Twenty-three of the 25 Comprehensive Environmental Response Compensation and Liability Act (CERCLA - EPA Super Fund sites) in the Puget Sound Basin are located in the 4 central Puget Sound counties, as are most of the EPA-regulated Resource Conservation and Recovery Act (RCRA) sites shown in figure 30 and Toxic Release Inventory (TRI) sites shown in figure 29. The industrial release of toxic chemicals in the Puget Sound Basin as reported by the TRI amounted to over 13 million pounds in 1992, nearly all of which were released to the atmosphere (table 6). Most CERCLA and RCRA waste sites are subject to site-specific investigation of surface- and ground-water quality, however, little information is available to assess the impacts of TRI atmospheric releases on the quality of water in the Puget Sound Basin.

Agriculture

More than 6 percent of the Puget Sound Basin, or about 540,000 acres, is occupied by agricultural land use (U.S. Department of Commerce, 1994). The distribution of agricultural lands is largely controlled by the locations of prime agricultural soils, most of which have been fully developed as agricultural or urban land. More than half of the agricultural acreage in the basin is located on the outwash deposits, alluvial valleys, and river deltas of Whatcom, Skagit, and Snohomish Counties (fig. 31). The Olympic Peninsula contains only 8 percent of the agricultural lands in the basin (table 7). In total, the Puget Sound Basin contains only about 3.4 percent of the total agricultural acreage found in Washington State, and this percentage is declining. From 1987 to 1992, the number of farms in the basin decreased by 11 percent (from 8,789 to 7,855) and the total acreage decreased by 5 percent (from 567,00 to 540,000 acres) (U.S. Department of Commerce, 1994). This general decline in agriculture can be attributed to the region's growing population, as urbanization increasingly competes for land, especially in the four-county central Puget Sound area.

There are more than 320,000 acres of cropland in the Puget Sound Basin, on which hay, corn, peas, potatoes, raspberries, wheat, and other crops are grown (table 7 and fig. 31). Orchards account for about 1,800 acres of land, and approximately 200,000 acres are devoted to pasture. Hay is grown on about 108,000 acres, and corn for silage is grown on an additional 20,000 acres. These crops are grown largely to support livestock. There are 956 dairy farms, with about 150,000 milk cows, and there are about 345,000 beef cattle in the basin (U.S. Department of Commerce, 1994). The basin also contains approximately 770 poultry farms.

Livestock in the Puget Sound Basin produces a large amount of manure that is generally applied to the land as a plant nutrient during the growing season. As shown in table 8, the amount of nitrogen and phosphorus from manure produced by livestock exceeds the amount of nitrogen and phosphorus applied as fertilizer. As with fertilizer, if manure is applied in amounts exceeding plant requirements or applied when plants cannot utilize it, such as during the nongrowing season, excess nutrients may leach to the ground water or wash off to streams, resulting in undesirable concentrations in water. Elevated concentrations of nitrate in the ground water underlying agricultural areas of Whatcom County are well documented (S.E. Cox, U.S. Geological Survey, written commun., 1996).

The use of chemical pesticides is often associated with agriculture. However, in the Puget Sound Basin, it was estimated in 1988 that only 12 percent (340,000 pounds) of the approximately 2,850,000 pounds of pesticides applied anually in the basin were used for agricultural purposes (Tetra Tech, 1988). Other major pesticide users include urban (residential, commercial, public agencies--1,080,000 lb/yr (pounds per year),

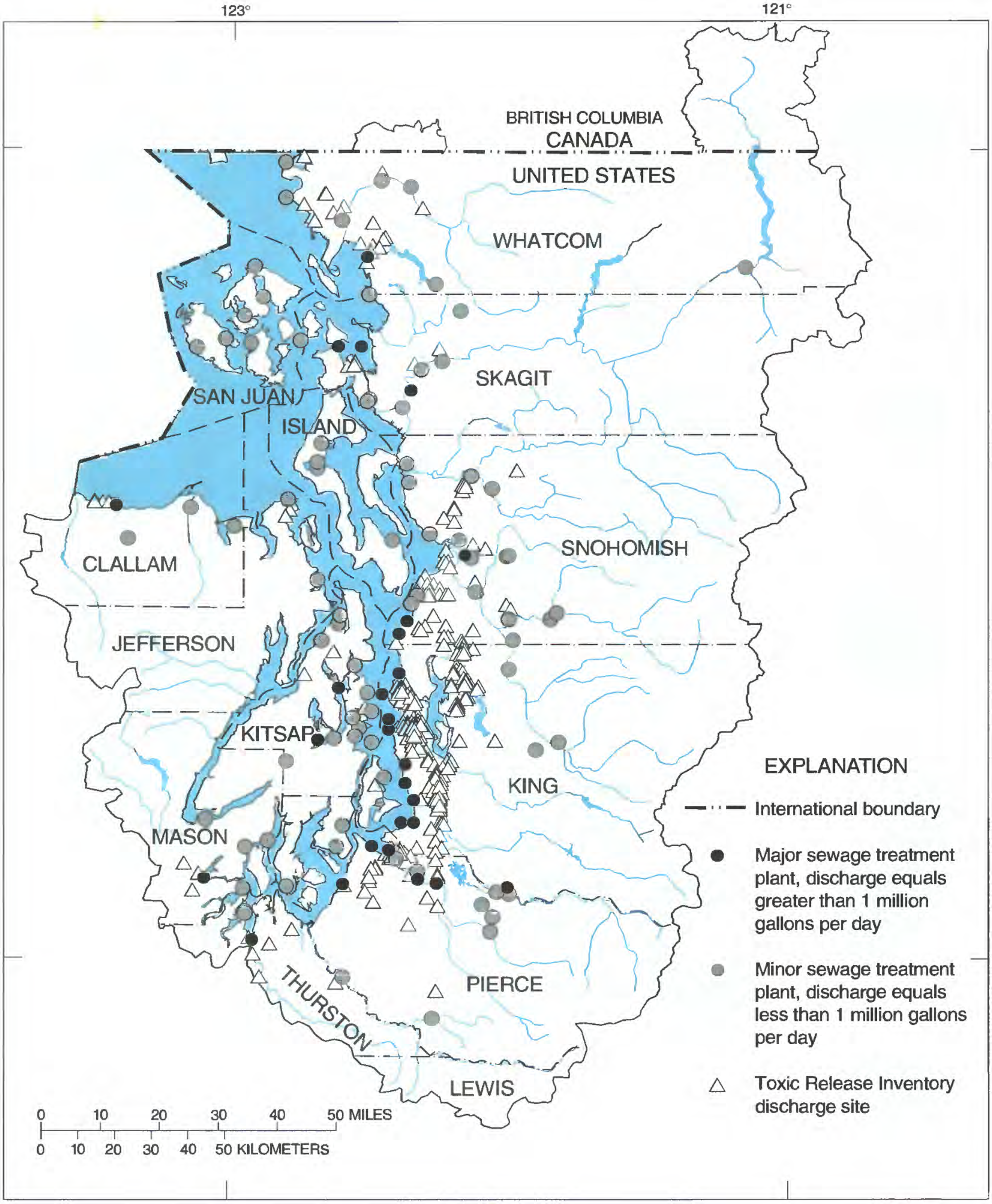


Figure 29. Locations of point source discharges in the Puget Sound Basin. (Toxic Release Inventory from U.S. Environmental Protection Agency, 1955a. Municipal discharge information from Washington State Department of Ecology, Wastewater Permit Life Cycle System, written communication, 1995.)

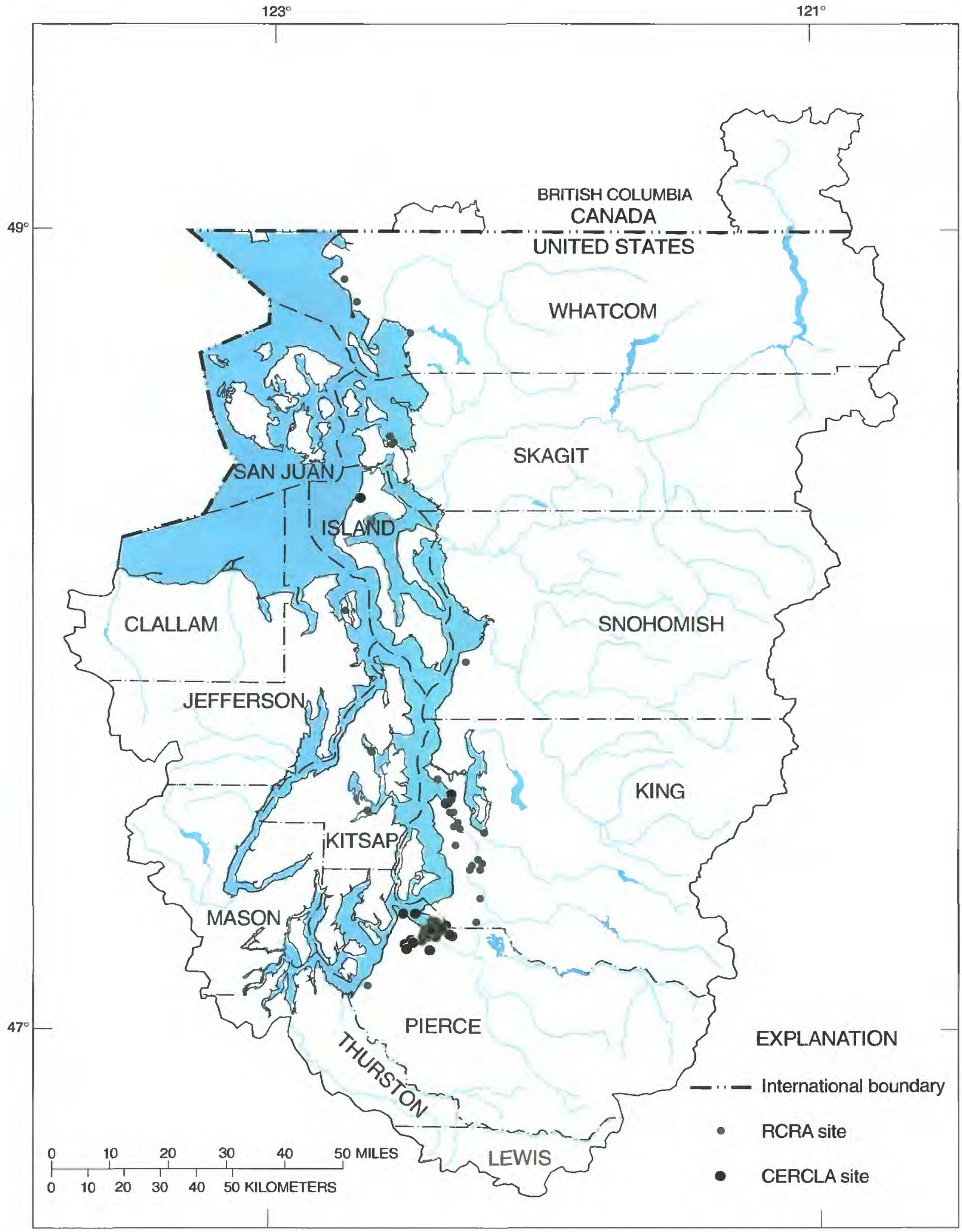
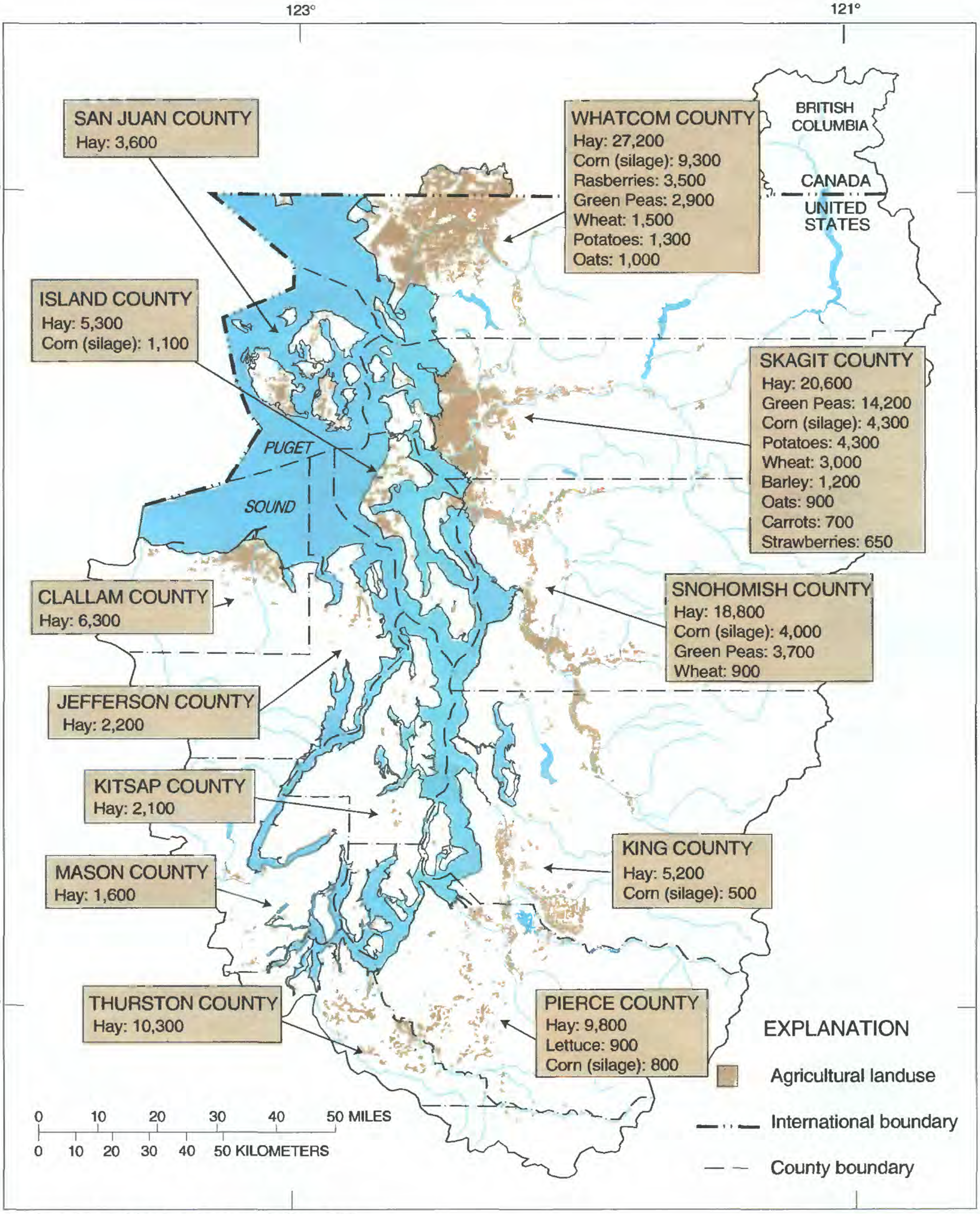


Figure 30. Locations of Comprehensive Environment Response Compensation and Liability Act (CERCLA) and Resource Conservation Recovery Act (RCRA) regulated hazardous-waste sites. (Data from U.S. Environmental Protection Agency, 1995b.)

***Table 6.**--Inventory of toxic chemicals released to the atmosphere and land in amounts greater than 1,000 pounds by industries in the Puget Sound Basin in 1992. All releases to water bodies were less than 1,000 pounds*

[Data from U.S. Environmental Protection Agency, 1992a; -- indicates no reported releases greater than 1,000 pounds]

Chemical	Releases (in pounds) to Atmosphere	Releases (in pounds) to Land
Methyl ethyl ketone	1,633,002	7,200
Methanol	1,359,248	--
Toluene	1,133,971	--
Acetone	1,131,543	--
Hydrochloric acid	909,770	--
Freon 113	692,001	--
Glycol ethers	683,788	--
Styrene	671,427	--
Xylene	604,745	--
1,1,1-trichloroethane	592,306	--
Chloroform	578,687	--
Sulfuric acid	528,101	--
Dichloromethane	458,115	--
N-butyl alcohol	446,825	--
Propylene	255,050	--
Trichloroethylene	247,260	--
Ammonia	168,984	--
Hydrogen fluoride	118,340	--
Methyl isobutyl ketone	113,687	--
Benzene	112,721	--
Chlorine	88,607	--
Creosote	71,262	--
Tetrachloroethylene	45,641	--
Dichlorodifluoromethane	45,240	--
Zinc compounds	44,156	--
Ethylbenzene	41,140	--
1,3-butadiene	40,499	--
1,2,4-trimethylbenzene	40,485	--
Cyclohexane	39,336	--
Ethylene	36,160	--
2-ethoxyethanol	21,100	--
Methyl tert-butyl ether	19,300	--
Chlorine dioxide	18,556	--
Napthalene	15,818	--
Ethylene glycol	10,881	--
Trichlorofluoromethane	6,654	--
Lead compounds	5,946	--
Nitric acid	5,513	--
Chromium	5,342	--
Formaldehyde	5,260	--
Cumene	4,141	--
Manganese compounds	3,911	--
Dicthanolamine	2,773	--
Phenol	2,728	--
Manganese	2,574	--
Phosphoric acid	2,355	--
Nickel compounds	1,495	--
Methylenebis (phenylisocyanate)	1,333	--
Mercury compounds	1,250	--
Nickel	1,250	--



Land use data modified from Fegeas and others, 1983.

Figure 31. Major agricultural crops (greater than 500 acres) raised in counties of the Puget Sound Basin, with crop values shown in acres. (Agricultural statistics from Washington Agricultural Statistics Service, 1994.)

Table 7.--*Agricultural acreage and livestock in the Puget Sound Basin, 1992*
[Data modified from U.S. Department of Commerce, 1994]

County	Total acreage (acres)	Change in acreage, 1987-92 (percent)	Cropland (acres)	Orchards (acres)	Cattle (number)
Whatcom	118,000	-5	90,700	329	171,100
Skagit	92,100	-3	72,600	207	72,000
Snohomish	74,200	-9	48,700	90	73,000
King	42,300	-22	3,900	168	57,300
Pierce	58,800	0	27,200	588	37,700
Thurston	59,900	+5	26,500	108	45,400
Mason	11,000	-6	3,900	33	2,700
Jefferson	9,600	-19	4,900	20	6,500
Clallam	24,300	-9	12,900	50	11,100
Kitsap	10,300	+7	3,900	67	2,700
Island	19,500	+4	14,500	42	11,300
San Juan	20,500	+14	10,900	110	4,600
Total	540,500	-11	320,600	1,812	495,400

Table 8.--*Nutrient loading from fertilizer and manure applications in the Puget Sound Basin*
[Data are from R.B. Alexander, U.S. Geological Survey, written commun., 1995]

	Manure produced, 1992 (short tons)		Fertilizer applied, 1991 (short tons)		
County	Nitrogen	Phosphorus	Nitrogen	Phosphate	Potash
Whatcom	7,500	1,200	3,400	1,000	700
Skagit	2,900	510	4,900	1,500	1,000
Snohomish	4,000	800	1,500	460	320
King	2,600	440	900	270	180
Pierce	1,900	390	860	180	260
Thurston	2,400	550	300	89	61
Mason	95	27	50	15	10
Jefferson	220	56	38	11	7
Clallam	420	100	236	70	49
Kitsap	140	36	0	0	0
Island	490	96	280	83	57
San Juan	170	47	61	18	13
Total	22,835	4,252	12,525	3,696	2,657

military installations (430,000 lb/yr), right-of-ways (transportation and utilities--270,000 lb/yr), and silviculture (21,000 lb/yr). The silviculture use estimates were based on only two major landowners and were noted to underestimate actual use; an additional 720,000 pounds of pentachlorophenol (used as a wood preservative) was noted as used at an undetermined number of sites in the basin (Tetra Tech, 1988). Table 9 lists the application rates of the 20 most commonly used pesticides in the Puget Sound Basin by county and notes the predominant use of the pesticide.

Forest

In 1970, forest lands covered approximately 6.8 million acres and occupied about 78 percent of the Puget Sound Basin, extending from sea level to the alpine reaches of the Cascade Range and Olympic Mountains. The forest is largely coniferous, and Douglas fir is the most common tree species. About one-half of the forest is managed for commercial timber harvest, and each year about 50,000 to 75,000 acres are harvested (Puget Sound Water Quality Authority, 1988). The most productive timber lands are found in the lowlands and in the lower altitudes of the mountains, where temperatures are higher and the growing season is longer. These forest lands have been extensively logged, and they currently support timber, wood products, and pulp and paper industries that are important to the local economy (Northwest Pulp and Paper Association, 1985). The Puget Sound Basin also contains many of the last remaining stands of old-growth forest (more than 180 years old) in the Pacific Northwest. The remaining old-growth forest and the ecosystem that it supports are largely contained within Federal lands managed by the U.S. Forest Service and the National Park Service.

Approximately 48 percent of the Puget Sound Basin forest land is federally administered public land (U.S. Forest Service, 1990). The U.S. Forest Service manages roughly 2.3 million acres, including about 2 million acres of the Mount Baker-Snoqualmie National Forest and 317,000 acres of the Olympic National Forest (fig. 32). These National Forest lands are mostly located in the Cascade Range and Olympic Mountains, and by law, they are managed for multiple uses, including timber production, range, outdoor recreation, water supply, and habitat preservation. National forests have a large fraction of timber in the older age classes, with approximately 56 percent of the timberland base 90 years or older (Adams and others, 1992). Recent management guidelines (U.S. Forest Service and U.S. Bureau of Land Management, 1994) adopted to protect spotted owl habitat in old-growth forests may substantially increase the amount of National Forest land that is held in reserve and is unavailable for timber harvest.

The National Park Service administers more than 1 million acres in the basin, including portions of the Mount Rainier (164,000 acres), Olympic (374,000 acres), and North Cascades (494,000 acres) National Parks. The forest land in these parks is managed as wilderness or for public recreation and is not available for commercial timber harvesting.

The Washington State Department of Natural Resources (DNR) is the third largest landholder in the Puget Sound Basin, administering approximately 600,000 acres of land (Pacific Northwest River Basins Comission, 1970a). Much of the State land is middle- to lower-altitude forest managed for timber production. About one-half of DNR's timber is less than 45 years old, and only 20 percent is over 70 years old (Adams and others, 1992).

Approximately 2.3 million acres of Puget Sound Basin forest is private commercial timberland (Adams and others, 1992). Private timberlands are generally concentrated in the most productive lower altitude areas and are managed primarily for timber production. This land is owned by a few large, mostly corporate landowners, who control about 1.1 million acres, and by many medium (300 acres or more) and small, rural or suburban landowners. The amount of private timberland in the basin has decreased by about 3 percent since 1965 as lowland forest has been developed for urban land uses.

IMPLICATIONS OF ENVIRONMENTAL SETTING FOR WATER QUALITY AND AQUATIC BIOTA

Previous sections of this report describe the natural and human features that make up the general environmental setting of the Puget Sound Basin. This information indicates that the rivers and streams draining to Puget Sound share many common characteristics. Most of the major rivers in the basin have their headwaters in forest-covered mountainous terrain that annually receives large quantities of precipitation. With the exception of extensive logging, the quality of water in the upper watersheds of these large rivers is only minimally affected by man, and these watersheds discharge large volumes of good-quality water to the lowlands during most of the year.

Table 9.--*Estimated annual pesticide applications in the Puget Sound Basin for pesticides with more than 22,000 pounds of annual use*

[Data from Tetra Tech, 1988 reported in pounds of active ingredient per year (lb/yr); NA, data not available]

	Quantity of pesticide applied, by county (lb/yr)												
	Clallam	Island	Jefferson	King	Kitsap	Mason	Pierce	San Juan	Skagit	Snohomish	Thurston	Whatcom	Total
Pentachloro-phenol[1,4]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	720,000
2,4-D[3]	5,249	2,397	3,717	25,219	4,342	2,583	214,313	1,917	11,340	18,106	6,329	11,574	311,406
Methyl Bromide[2]	5,300	4,500	1,600	130,600	15,100	3,200	50,000	800	6,600	34,700	12,800	11,000	276,200
Malathion[3]	1,562	2,028	476	38,010	4,354	936	136,935	240	1,912	10,048	3,672	3,153	203,326
Sulfuryl Fluoride[2]	2,300	2,000	700	57,100	6,600	1,400	21,900	400	2,900	15,200	5,600	4,800	120,900
Prometon[4]	90	80	30	28,324	281	13,023	20,382	15	6,581	7,107	235	32,596	108,744
Simazine[3]	144	188	42	19,708	868	50,083	11,494	13	1,184	9,681	1,266	2,612	97,283
Diazinon[3]	1,666	1,416	512	39,647	4,607	1,004	14,874	245	2,123	9,538	3,967	3,528	83,127
Dicamba[3]	225	1,387	68	19,246	1,640	2,325	15,106	25	5,096	6,089	637	3,602	55,446
Triclopyr[4]	766	285	79	7,845	871	170	36,356	25	600	4,543	1,573	720	54,633
Metaldehyde[2]	1,000	900	300	26,100	2,900	600	9,400	200	1,300	6,800	2,500	2,200	54,200
Chlorodane[2]	1,000	800	300	23,500	2,700	600	9,000	100	1,200	6,300	2,300	2,000	48,900
Atrazine[3]	17	396	0	18,328	2,000	80	3,387	0	4,389	3,101	1,651	3,582	44,391
Bromacil[3]	0	14,397	240	323	321	28	15,097	0	174	140	10,014	83	40,817
Chlorpyrifos[2]	800	700	200	18,500	2,200	500	7,200	100	900	4,900	1,800	1,600	39,400
Carbaryl[3]	773	564	242	14,150	1,589	394	5,484	87	4,991	4,550	1,412	3,061	37,297
Diuron[3]	113	13,758	400	5,374	1,045	1,095	3,478	0	803	2,712	1,167	305	37,120
Glyphosate[3]	782	481	422	11,889	1,267	299	9,209	59	1,089	5,722	1,583	2,286	35,088
Sulfur[2]	700	600	200	16,400	1,900	400	6,300	100	800	4,400	1,600	1,400	34,800
Tebuthiuron[4]	0	0	0	8,272	0	4,130	6,192	0	2,064	2,064	0	10,321	33,043

[1] Total includes pesticide usage basin-wide; no county data available.

[2] Primarily urban use.

[3] Primarily agricultural use.

[4] Primarily other use (forestry, right-of-way management, etc.)

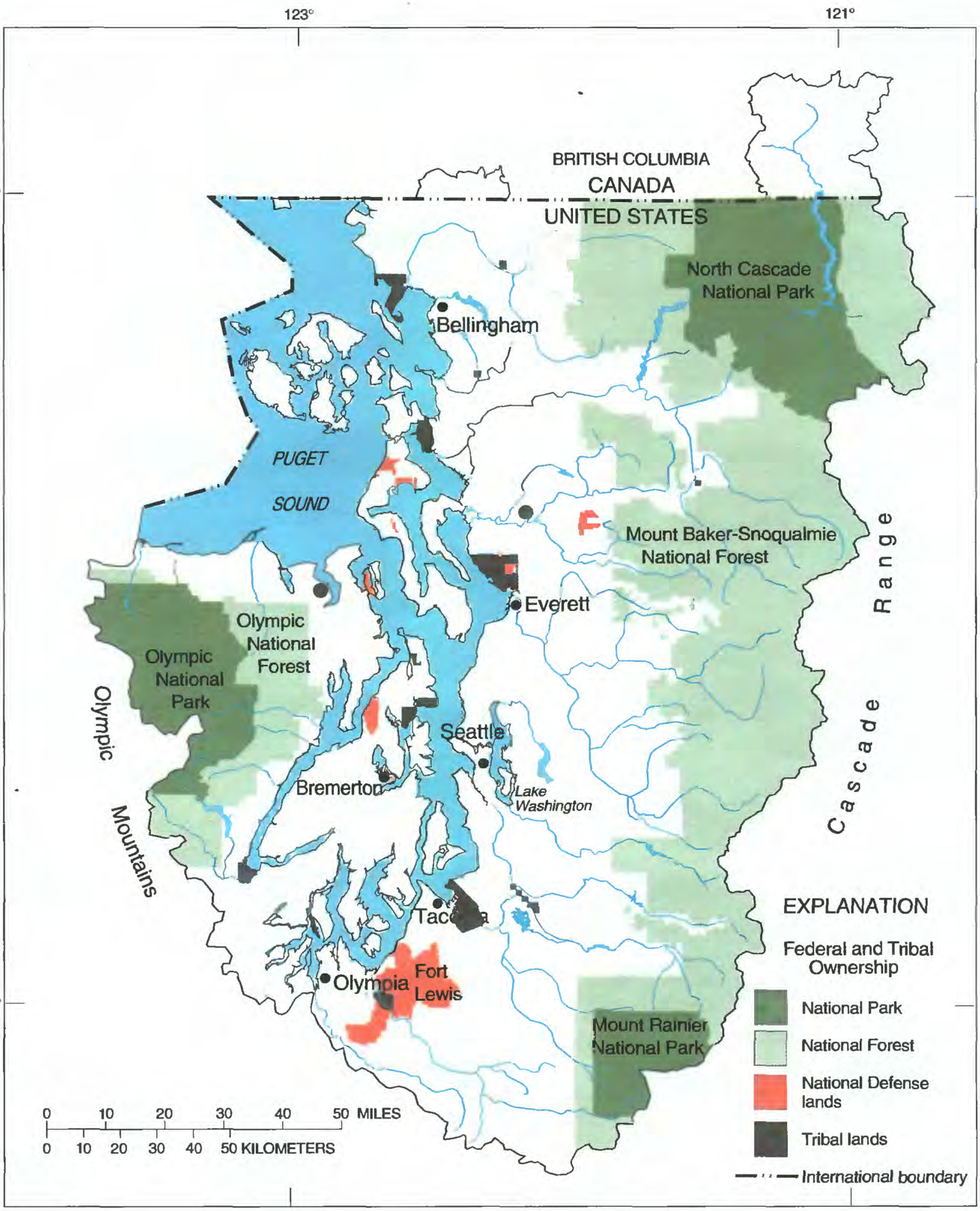


Figure 32. Major Federal and Tribal land ownership in the Puget Sound Basin.

Most settlement in the Puget Sound Basin is in the lowlands along the shores of Puget Sound and in the lower alluvial valleys, and most of the human impact on water quality occurs in these areas. Smaller lowland streams draining these developed areas are most prone to contamination resulting from urban and agricultural runoff. Large rivers are less prone to contamination in all but the most developed basins due to the large volume of mountain runoff carried by the rivers and the relatively short distance they traverse the lowlands. Most municipal and industrial point sources and combined sewer overflows discharge to the lower tidal river reaches or directly to Puget Sound. Consequently, the most frequent detections of toxic contaminants occur in the saltwater bays and estuaries near the major cities. In the fresh-water system the physical water-quality characteristics of stream temperature, suspended sediment concentration, and in-stream habitat have been significantly affected by a range of forestry, agricultural, and urban development practices, and these impacts have been observed in small streams and large rivers from the mountain headwaters to the agricultural and urban lowlands.

Ground water is also an important resource in the Puget Sound Basin and provides about 40 percent of the drinking-water supply. The Puget Sound aquifer system is contained largely within the alluvial and glacial outwash deposits of the Puget Sound Lowland. These aquifers vary in composition and in their susceptability to contamination. The shallow alluvial aquifers and the unconfined outwash aquifers are most susceptable to contamination, and in areas where these aquifers are overlain by urban and intensive agricultural land uses, elevated nitrate concentrations have been found in ground water.

The following section of this report summarizes the water-quality conditions in the Puget Sound Basin and notes the influence of the region's environmental setting on both surface- and ground-water quality. The natural background quality of water is described, the possible source of contaminants and human influences in the upper forested and lower urban and agricultural watersheds is discussed, and the results and conclusions of past water-quality investigations are summarized.

Water-Quality Influences from Natural Factors

In the absence of human civilization and development, natural background variations in water quality are largely controlled by the variety of landforms, climate, and earth materials that are present locally, the natural chemical weathering of earth materials, and the transport energy of the hydrologic system. The combination of these factors defines local stream morphology, water temperature, concentration of chemical constituents in water, and the structure of the aquatic ecosystem that has adapted to the natural range of variability of these conditions.

Surface Water

The Puget Sound Basin has moderate to high annual precipitation in the mountainous headwater reaches, and surface water draining these reaches is chemically dilute. The dissolved-solids concentrations are broadly similar for all rivers in the basin (Dethier, 1982). Concentrations of dissolved-chemical constituents in surface waters are generally small throughout the year, but the smallest concentrations occur during spring runoff and after rain storms. Dissolved-solids concentrations can be represented by specific conductance values that have been found by Hopkins (1993) to be low; medians for a 12-year period (1979 to 1991) ranged from 45 to 128 μs/cm (microsiemens per centimeter) for major rivers draining to Puget Sound. The background chemical quality of most surface water throughout the Puget Sound Basin is good or excellent and suitable for most uses (Washington State Department of Ecology, 1992). Many of the upper watersheds in the region supply water that requires minimal treatment to the region's largest cities.

Natural suspended-sediment concentrations are highly variable in Puget Sound Basin streams. Sediment discharge is sensitive to increases in streamflow. During low streamflow, suspended-sediment concentrations often are less than 5 mg/L (milligrams per liter) , and increase to 500 mg/L or more during high streamflow (Nelson, 1971, 1974). Annually, under natural conditions, most sediment is transported in a few days during periods of winter storms (Richardson and others, 1968; Nelson, 1971, 1974). Relatively little sediment is eroded from lowlands; most of the sediment originates in the mountains during storms, according to Nelson (1974). Streams fed by glacial meltwater, however, are often turbid and sediment-laden for longer periods, particularly in mid to late summer. Natural turbidity is high in the major rivers and smaller streams draining glaciers in the Nooksack, Skagit, Puyallup, and Nisqually Basins (fig. 1).

Under natural conditions, stream temperatures in the basin are rather cool throughout most of the year because of generally cool air temperatures, shading from a dense forest canopy, and snowmelt from mountainous terrain (Hidaka, 1972; Collings and Higgins, 1973). The highest stream temperatures occur in July and August, coinciding with highest air temperatures and low flow.

Ground Water

Most ground water in the Puget Sound Basin is soft (60 mg/L as $CaCO_3$ or less) or moderately hard (61 to 120 mg/L as $CaCO_3$), and the concentrations of dissolved solids in ground water are well below the secondary maximum contaminant level (MCL) for drinking water of 500 mg/L (U.S. Environmental Protection Agency, 1992b). Typically, concentrations of dissolved solids in the region's ground water are less than 150 mg/L (Turney, 1986). Large concentrations of dissolved solids are found in waters from few and widely separated areas and are generally attributed to ground-water production from aquifers in marine sedimentary deposits (Van Denburgh and Santos, 1965).

Dissolved iron and manganese are two natural constituents of concern in the ground water of the Puget Sound Basin (Foxworthy, 1979; Turney, 1986; and Embrey, 1988). Water from 186 of 1,376 wells (14 percent) in the study unit exceeded the dissolved iron secondary MCL for drinking water of 500 μg/L (micrograms per liter) (U.S. Environmental Protection Agency, 1992b). Some type of treatment to remove or reduce the effects of dissolved iron is a common practice when ground-water supplies are developed in the region (Foxworthy, 1979). Although dissolved iron and manganese concentrations commonly exceed standards, other minor and trace elements rarely do, according to Turney (1986), who sampled more than 100 wells and springs in the Puget Sound region. Some large concentrations of zinc, copper, and lead have been observed in sampled ground water in the region, but Turney believed that these concentrations were probably due to contamination from the plumbing of water distribution systems. Stewart and others (1994) substantiated Turney's finding from data compiled from 3,700 wells statewide; they found relatively few ambient waters had elevated concentrations of trace elements. Most of the elevated levels of trace elements in ambient waters of the Puget Sound Basin are the naturally occurring elements of arsenic and selenium (Stewart and others, 1994). In eastern Snohomish County, elevated arsenic and selenium concentrations have been attributed to natural processes (Snohomish Health District and Washington State Department of Health, 1991). Water from many wells in the Puget Sound Basin also contain naturally large concentrations of orthophosphate phosphorus--commonly more than 0.20 mg/L. Orthophosphate phosphorus concentrations increase in water with increased geologic age and depth of the aquifer, and therefore they are believed by Van Denburgh and Santos (1965) to be derived from the natural dissolution of phosphate-containing rock. These concentrations of phosphorus in ground water should not affect drinking water and most other uses.

Water-Quality Influences from Human Factors

Human influences on water quality are generally controlled by how the land and water are used and how wastes and other by-products of human activities are managed. Land use in the Puget Sound Basin differs greatly between the upper forested watersheds of the Olympic Mountains and the Cascade Range and the lower agricultural and urbanized watersheds of the Puget Sound Lowland, and the water-quality issues in these parts of the basin differ accordingly.

Stream reaches in the Puget Sound Basin have been classified by the Washington State Department of Ecology (Ecology) as threatened, impaired, or fully supported. The stream classification is based on its beneficial use status. For example, an impaired stream is one that does not have the necessary quality to support or allow the beneficial uses of the water as defined by the State's criteria (Washington State Department of Ecology, 1989). Streams draining the upper watersheds, in general, fully support their intended use, and other streams (mostly in lowland areas) are variously categorized as threatened or impaired (Washington State Department of Ecology, 1989). Many stream reaches, including some streams in the upper watersheds, are less than fully supported because of naturally occurring suspended sediment from glacial meltwater.

Upper Watersheds

The upper watersheds of the Puget Sound Basin are largely composed of uninhabited, forested, and mountainous terrain. Ground water in the upper watersheds is little used, and its quality probably differs little from natural background conditions. The chemical quality of surface water in the upper watersheds is usually suitable for most uses. However, the physical hydrology, water temperature, and biologic integrity of streams have been influenced to varying degrees by logging, and water quality may have been influenced to some limited degree by deposition of contaminants released to the atmosphere in the urbanized lowlands.

Substances released to the atmosphere by fossil-fuel combustion and various industrial activities are brought to the land surface in rain and dry fallout. Motor vehicles account for 55 percent of air emissions (Washington State Environment 2010, 1992) in the Puget Sound Basin. Other major air pollution sources include industry, outdoor burning, and wood-stove burning. Motor vehicles and fossil-fuel burning produce nitrogen oxides and sulfur dioxide particulates. These combustion products carried in the atmosphere combine with water to produce nitric and sulfuric acids in rain.

Lakes from 29 watersheds were sampled for evidence of acid precipitation in the central Cascade Range in Washington by Logan and others (1982). All of the lakes sampled were found to be sensitive to lake acidification but had not become acidic. Sulfate concentrations in snowpack collected from the Cascades in Washington were found by Laird and others (1986) to be influenced by major metropolitan areas. However, these authors concluded that the snowpack in the Cascade Range was not strongly influenced by human activities at the time of sampling in 1983. An earlier study by Dethier (1979) indicated that bulk precipitation contributed significant quantities of cations and trace metals to a subalpine catchment located in the north-central Cascades. A study in the North Cascade National Park by Funk and others (1987) concluded that concentrations of chlorides, sulfates, and trace metals were not found in streams and lakes in the park much above those believed to be naturally present. In 1983, Turney and others (1986) also found that lakes in Mount Rainier National Park were sensitive to acidification but had not become acidic. Little or no data exist concerning the deposition and occurrence of toxic organic compounds in the upper watershed resulting from atmospheric releases in the lowlands as reported by the EPA's Toxic Release Inventory (fig. 29 and table 6).

Logging and associated road building are common throughout the upper watersheds of the Puget Sound Basin. The effects on streamflow and water quality due to logging depend on a number of factors such as percentage of a basin cut, method of harvest, road maintenance, forest chemical applications, and proximity to streams, wetlands, and shorelines. Principal water-quality concerns due to logging are erosion of soils (causing increased sediment loading to streams), removal of the forest canopy near streams (causing elevated stream temperatures), increased nutrient yields following harvest, and application of forest chemicals (causing toxicity to aquatic biota). Most studies have discussed clear-cut logging and constructing roads in mountainous terrain as potentially contributing to sediment transport (Harr, 1986), but MacDonald and others (1991) have pointed out that absolute changes in the rate of sediment transport after logging are difficult to measure because of the need to intensively sample high-flows and the difficulty of obtaining accurate results. Comparing differences in runoff between paired basins (logged and unlogged) is often difficult, as documented by the lack of measurable differences in runoff patterns of small paired basins in the upper Green River Basin (Richardson, 1965). Richardson explained that long-term or cumulative effects of continued logging may not have been measurable because the logged basin was cut in parcels over time during the study. A number of more recent paired-watershed experiments have shown that logging usually has an effect on streamflow patterns (MacDonald and others, 1991). The magnitude of peak flows after logging is believed to increase in areas subject to rain-on-snow melt events (Berris and Harr, 1987; Washington Forest Practices Board, 1994). A consequence of higher peak flows is discussed by Harr (1986) who states that "higher peak flows indicate a higher rate of water delivery to soils, which, in turn, suggests increased potential for both hillslope and channel erosion." Within the U.S. Forest Service's 20,000-acre Canyon Creek watershed located within the Nooksack River Basin, approximately 600,000 cubic yards of sediment was estimated to have entered headwater streams within a 10-year period as a result of unstable stream banks. Most of the unstable stream banks were associated with human activities such as road construction and logging (U.S. Forest Service, 1995a). Additional studies within the Canyon Creek watershed identified 100 landslides that occurred from 1940 to 1990, 73 of which occurred after 1970. Seventy-three percent of the landslides occurred in clearcuts or roadcuts, and 50 percent of these added sediment directly to streams (U.S. Forest Service, 1995a). A similar trend in landslide occurrence was observed in the South Fork of the Stillaguamish River Basin (U.S. Forest Service, 1995b).

Increases in stream temperatures and nutrient yields after logging are well documented for small watersheds (<1.5 mi^2) according to Anderson (1973) and Geppert and others (1985). Stream temperature effects are particularly significant if logging extends into the riparian zone. Nitrogen concentrations and stream temperatures of small watersheds were found to increase for 3-5 years following logging and to return to prelogging levels within 5 to 10 years (Harr and Fredricksen, 1988). The cumulative effects of logging on large streams (greater than 100 mi^2

drainage area) is less clear because the watersheds are cut in parcels over a long period. Paul (1996) reports that the natural variability in climate and hydrology over a 5 to 10 year period also may mask the nutrient and temperature effects of logging within these larger watersheds.

Modern forest practices utilize chemicals that may include herbicides, insecticides, fertilizers, fire retardants, and carriers for pesticides. Forest pesticides were monitored for their entry into surface waters by aerial application by Rashin and Graber (1993). Maximum pesticide concentrations, excluding runoff events, of triclopyr, 2,4-D, glyphosate, imazapyr, chlorothalonil, and metasystox occurred within the first 3 hours from over-spray (Rashin and Graber, 1993). These chemicals may vary considerably in their likelihood to enter surface waters or cause ecological harm, and their cumulative effect on larger streams is not known.

Lakes and streams in upper watersheds of the Puget Sound Basin may be susceptible to water-quality degradation from recreational use of trails and campsites. The most likely pollutants from recreational activity are nutrients and pathogens from human or livestock waste and sediment (Gilliom and others, 1980). Wet areas in alpine meadows are probably the most important single land cover that affects the transport of pollutants to lakes and streams (Gilliom and others, 1980). Symptoms of nutrient enrichment were not observed in alpine lakes in the region in the late 1970's (Dethier and others, 1979, Bortleson and Dion, 1979; Gilliom and others, 1980) but the potential exists for excessive nutrient loadings due to increased recreational activity.

Mining and gravel extraction in the upper watersheds of the Puget Sound Basin may have altered habitat and water quality in streams locally (MacDonald and others, 1991; Fuste' and Meyer, 1987). Some small headwater streams may be affected by mining; however, due to its limited extent within the Puget Sound Basin, mining likely has little widespread effect on water quality. Gravel extraction from stream channels is common within the basin and may have wider ranging effects. The rate of gravel removal after two or three decades of extraction from three rivers draining the southern Olympic Mountains (outside the Puget Sound Basin) was found to exceed the rate of supply by more than tenfold (Collins and Dunne, 1989). According to the authors the differences between supply and removal were accommodated by lowering or scouring the channel, which could adversely affect fish habitat.

Lower Watersheds

The influence of human activity on the quality of water in the lower watersheds of the Puget Sound Basin can be relatively simple and direct, such as point-source discharges of waste to surface or ground water, or more subtle and complex, such as nonpoint-source runoff or infiltration to ground water. Approximately one-half of contaminant loadings to Puget Sound are estimated to come from industrial and municipal point sources, and the other half comes from nonpoint sources of pollution (Puget Sound Water Quality Authority, 1992). Most point-source discharges are made directly to Puget Sound or to the tidal reaches of its tributaries. Nonpoint sources are therefore of proportionately greater importance to the basin's freshwater system. Nonpoint sources are diffuse and often consist of many small sources of pollution that have a cumulative effect. Examples of nonpoint sources include urban runoff, seepage from on-site septic systems, infiltration or washoff of land applied manure, fertilizer, or pesticides, and deposition from atmospheric sources. Nonpoint sources affect the quality of surface and ground water most significantly in the agricultural and urban areas of the Puget Sound Lowland.

Surface Water

Overall, the quality of streams in the lowlands meets water-quality standards for most water uses; however, water-quality standards are frequently not met for fecal-coliform bacteria and stream temperatures and occasionally for dissolved oxygen (Washington State Department of Ecology, 1994). Concentrations of suspended sediment in glacially-fed streams commonly do not meet standards (Washington State Department of Ecology, 1994). Concentrations of nutrients and toxic contaminants, such as trace elements and synthetic organic compounds, commonly meet water-quality standards (Washington State Department of Ecology, 1989). However, standards do not exist for most synthetic organic compounds.

Fecal-coliform standards commonly are not met in both streams and estuaries of the basin (Washington State Department of Ecology, 1994). Streams are considered the dominant source of fecal-coliform bacteria reaching estuaries (Puget Sound Water Quality Authority, 1986). The highest fecal-coliform counts occur in streams after heavy rains; consequently, concentrations of fecal-coliform bacteria in estuaries and shellfish increase after rainstorms (Puget Sound Water Quality Authority, 1986). Sources of fecal bacteria contamination are most commonly failing septic tanks, washoff of animal manure, discharge from CSOs, and urban runoff.

During July and August, stream temperatures have been found to be higher than the freshwater standard of 18 degrees Celsius for class A (rated excellent) waters of several major rivers--Stillaguamish, Snohomish, Sammish, and Cedar Rivers (fig. 1) (Washington Administrative Code, 1992; Hopkins, 1993). For these rivers, on average, the temperature standard was exceeded by 2 to 4 degrees Celsius. Summer temperatures that exceed standards occur in the lower reaches of the non glacially-fed rivers. In contrast, several major rivers (Nisqually, Puyallup, and Skagit) fed by major glaciers are not known to violate temperature standards.

Streams in the region occassionally can be impaired by large total phosphorus concentrations. Excessive phosphorus in the region's streams can lead to an imbalance in natural cycles and cause eutrophication (Gilliom and Bortleson, 1983). The hypothesis that phosphorus is the limiting nutrient for most streams in the region is based on high dissolved nitrogen-to-phosphorus ratios observed for 36 streams in the region (Gilliom and Bortleson, 1983). Thus, management practices that control phosphorus sources are most important to control eutrophication of the region's streams.

Even though water-quality standards for nutrients are met for most streams, nitrogen loads for major rivers are important to receiving waters such as Puget Sound and the regions many lakes. Nitrogen loads vary considerably in the basin (S.S. Embrey, U.S. Geological Survey, written commun., September 1995). Loads for nitrogen and phosphorus were estimated for about 20 streams in the region by Embrey, who used data largely from the Washington State Department of Ecology's ambient monitoring program (Hopkins, 1993). As expected, nitrogen loads were greatest for the Skagit, Snohomish, and Puyallup Rivers (fig. 1), which have the largest watersheds and greatest water discharge. Nitrogen yields (load adjusted for watershed size) varied from 0.3 to 3.2 tons per square mile per year. Streams with nitrogen yields greater than 2.5 tons per square mile per year were Issaquah Creek, a small stream draining to Lake Sammamish, and the Cedar and Samish Rivers (fig. 1). In general, the lower nitrogen yields occurred in streams draining the less developed Olympic Peninsula and the southern part of the basin, and the higher nitrogen yields occurred in streams draining the Cascade Range and Puget Sound Lowland in the more developed part of the basin. These greater nitrogen yields result from the greater amounts of animal manure and fertilizer that are applied to the agricultural and urban lowlands and greater atmospheric nitrogen releases from automobile exhaust that occur in the more developed parts of the lowlands. In contrast to nitrogen yields, phosphorus yields (0.1 to 0.4 tons per square mile per year) were less variable throughout the region and showed few discernible patterns (S.S. Embrey, U.S. Geological Survey, written commun., September 1995).

Urban land use has a significant impact on the quality of streams in the Puget Sound Basin. Water-quality concerns related to urbanization include adequate sewage treatment and disposal, storm runoff and urban drainage, overflows from combined sewers, and preservation of stream corridors, especially small streams. As the Puget Sound Basin becomes more urbanized, stormwater control is considered one of the key issues in developing areas (Puget Sound Water Quality Authority, 1994). The Puget Sound Water Quality Authority (1994) estimates that the volume of untreated stormwater runoff is five times greater than the volume of treated discharges from sewage and industrial plants. Nonpoint sources of pollution are considered the most troublesome to maintain good water quality, according to King County Surface Water Management Division (1993). For example, in the Cedar River Basin (fig. 1) nonpoint sources of pollution to the main stem of the river and to its tributaries result from housing developments, road construction, on-site sewage disposal, livestock-keeping activities, gravel extraction, and hazardous waste sites. Other potential sources of nonpoint pollution are pesticide applications, underground storage tanks, small-quantity hazardous waste generators, and pipelines (King County Surface Water Management Division, 1993). Degradation of habitat in streams is also a common problem in urban areas (King County Surface Water Management Division, 1993).

Water-quality samples have been collected from a relatively large number of streams and small lakes in the urban-suburban part of King County (fig. 1) from the 1960's to the present by King County Department of Metropolitan Services (Metro). The quality of streams in western King County probably provides a representative characterization of water-quality conditions and trends for other parts of the Puget Sound Basin that are undergoing urbanization. During 1990-1993, stream sites in King County were rated as very good, good, fair, and poor on the basis of comparisons among all sites (King County Department of Metropolitan Services, 1994). Few stream reaches had consistently poor water quality, but many stream reaches did not meet standards for fecal coliform bacteria. The major factor that seems to control the water quality of streams is land use, according to Metro authors. They found that stream reaches with the best water quality are in the less developed watersheds. On the basis of benthic invertebrate population studies, in 1991, Metro rated 11 sites as very good, 9 sites as good, and 8 sites as fair (King County Department of Metropolitan Services, 1994). None of the sites were rated poor either year. The fair ratings were usually due to the presence of a low diversity of benthic invertebrates in bottom sediments (King County Department of Metropolitan Services, 1994).

Earlier studies by Metro in the 1980's indicated many of the priority pollutants in urban runoff originate from motor vehicles, and the pollutants adhere to the fine particles in street dirt (Galvin and Moore, 1982). Some of these particles contain trace elements and organic compounds that are transported by storm runoff to streams, lakes, and Puget Sound. In Seattle, the most frequently detected organic compounds in stormwater runoff were pesticides, pentachlorophenol, and polycyclic aromatic hydrocarbons (Galvin and Moore, 1982). Polycyclic aromatic hydrocarbon compounds originate from petroleum-based products such as lubricants, gasoline, and hydraulic fluids that commonly drip from vehicles on urban streets and parking areas (Galvin and Moore, 1982). Pentachlorophenol is commonly used in wood products, such as telephone poles, to prevent microbial and fungal decay. A study by Mar and others (1982) demonstrated that contaminants from urban runoff in Seattle were not generally associated with initial runoff "first flush" during storm flows. The lack of first-flush behavior was explained by Mar and others (1982, p. 15) as follows:

"...the rainfall and subsequent runoff patterns observed in western Washington are quite different from national patterns. Rainfall is of low intensity and long duration. A large initial flush of runoff to wash accumulated solids from the drainage system is uncommon. Instead, the runoff volume slowly increases and any accumulated solids are gradually carried from the system."

The lower, tidally-affected reaches of three major rivers in the basin (Snohomish, Green, and Puyallup Rivers) flow through urban centers of Everett, Seattle, and Tacoma, respectively (fig. 1). The water quality in the lower reaches of these rivers is adversely affected by storm water discharges and urban runoff. Ebey Slough, one of the distributary channels of the lower Snohomish River (fig. 1), is sufficiently depleted of dissolved oxygen to be listed as impaired for fish rearing, spawning, and harvesting (Thornburgh, 1993). Other water-quality problems of the lower reaches of Snohomish River are large concentrations of bacteria and suspended sediment according to Thornburgh. A study by Municipality of Metropolitan Seattle (1982) indicated that the suitability of the Green River for most water uses was rated generally good to excellent upstream of urban development, which starts in the City of Auburn about 30 miles upstream of the river mouth (fig. 1). In contrast, downstream of Auburn, the physical, chemical, and biological aspects of the river deteriorate where the river flows slowly at low gradient through an urban, and industrial setting before entering Puget Sound. The Duwamish Waterway of the lower Green River (fig. 1) is considered the most chemically contaminated of the three urban estuaries in Puget Sound (McCain and others, 1990, and Stein and others, 1995). The potential for uptake of toxic chemicals by juvenile chinook salmon in the Duwamish Waterway was examined by McCain and others (1990). These investigators found the mean concentrations of aromatic hydrocarbons to be about 650 times higher and polychlorinated biphenyls to be about four times higher in the stomach contents of salmon from the Duwamish Waterway than those in salmon from the Nisqually River (fig. 1), a reference site. Ebbert and others (1987) found that water quality in most of the lower Puyallup River has been only moderately affected by the activities of man; however, some degradation of water quality, as measured by increased concentrations of organic and inorganic compounds, was observed downstream from river mile 1.7 where a municipal wastewater-treatment plant discharges into the river.

Pesticide use in urban areas is extensive. A review by Tetra Tech (1988) indicates that the highest usage rates are for major urban counties (Pierce and King) followed by the major agricultural counties (Snohomish, Whatcom, and Skagit) (table 9). The pesticides of primary concern that may be transported to riverine and marine waters, according to Tetra Tech (1988), are 2,4-D, dicamba, alachlor, tributyltin, bromacil, atrazine, triclopyr, carbaryl, and diazinon. In 1992, two small urban streams (Thornton and Mercer Creeks) in the Lake Washington drainage were sampled for 162 pesticides and breakdown products by the Washington State Department of Ecology (Davis, 1993). From the large suite of pesticides analyzed, 10 different pesticides were detected in the urban streams sampled, and 2,4-D, DCPA, diazanon, dichlobenil, and glyphosate were detected in both of the streams. Diazanon, 2,4-D, and dicamba were also detected in water samples collected from Mercer Creek and Swamp Creek (a suburban stream draining to Lake Washington) by an earlier reconnaissance survey by the EPA (PTI Environmental Services, 1991).

Concentrations of selected trace elements collected in bed sediments at the mouths of 20 urban streams did not exceed most sediment-quality guidelines for benthic organisms (King County Department of Metropolitan Services, 1994; Bennett and Cubbage, 1991). However, the concentrations of trace elements from bed sediments of many urban streams were larger than concentrations from bed sediments of a relatively clean environment. Ebbert and others (1987) also found that bed sediments from small streams in the urbanized part of the Puyallup River Basin near Tacoma (fig. 1) contained more arsenic, lead, and zinc than background uncontaminated sites in the same basin. However, Galvin and Moore (1982) observed that streams receiving urban runoff did not necessarily contain contaminated bed sediments because erosion of cleaner sediments tends to mix and dilute organic compounds and trace elements bound to fine particles, which prevents buildup to toxic levels (Galvin and Moore, 1982). In 1992, Ecology analyzed pesticides in bed-sediment and fish-tissue samples from Mercer Slough, a channelized urban wetland in the Lake Washington drainage (fig. 1) (Davis and Johnson, 1994). Mercer Slough receives runoff from much of south Bellevue (fig. 1). Pesticides detected in bed sediments were DDT, five metabolites of DDT, chlordane, and dichlobenil. DDT, metabolites of DDT, and chlordane were among the pesticides detected in fish tissue from Mercer Slough (Davis and Johnson, 1994).

Lakes in the region have a wide range of nutrient conditions and land use settings. Excessive nutrient enrichment, causing nuisance growth of algae and rooted aquatic plants, has been observed in many lowland lakes that have residential and other land development within their drainage basins (Bortleson and Foxworthy, 1974; Bortleson, 1978). Urban runoff from new development is probably influencing the water quality of small lakes (King County Department of Metropolitan Services, 1994). The majority of small lakes studied by Metro are in an urban-suburban land use, and most of these lakes are moderately enriched with nutrients. Metro's long-term survey of lakes in King County showed a gradual increase in phosphorus nutrients from 1985 to 1993 and a corresponding decrease in water clarity resulting from denser algae populations (King County Department of Metropolitan Services, 1994). Lakes receiving urban runoff also are likely to have contaminated sediments. In Lake Washington (fig. 1), for example, bottom sediments contain elevated concentrations of organic compounds and trace elements (Galvin and Moore, 1982). Likewise, the bottom sediments of Lake Union in Seattle have elevated organic compounds and trace elements from stormwater runoff, sewers, and industrial sites along the shoreline (Washington State Department of Ecology, 1989). Copper was found in large concentrations in the bed sediments of Steilacoom Lake, a eutrophic urban lake near Tacoma (fig. 1). The primary source of copper in the bed sediments is copper sulfate applied as an algicide for many years (Bennett and Cubbage, 1992).

Urban land use also has a direct influence on Puget Sound. Contaminants entering the marine waters of Puget Sound that concentrate in the sediments generally do not flush out to the ocean. The largest concentrations of contaminants in the marine surface sediments occur in urban embayments (Puget Sound Water Quality Authority, 1992). Bed sediments of urban embayments of Puget Sound contain elevated concentrations of trace elements and organic chemicals (Crecelius and others, 1989). Contamination of marine sediments in urban embayments provides evidence of human impacts, but only limited data are available to track sources and estimate the relative contribution from multiple sources. Martin and Pavlou (1985) identified sources of marine bed-sediment contamination as riverine, shoreline erosion, atmospheric origin, and municipal and industrial discharges.

Although occupying only about 6 percent of the basin, agricultural land use can have a significant impact on the quality of fresh water in the Puget Sound Basin. Nonpoint pollutants often identified with agricultural runoff are sediment, nutrients, pesticides, and bacteria. Crop production can introduce pollutants into a stream system by disturbing the soil and removing vegetation, or through application of fertilizers, insecticides, and herbicides. Animal production activities can degrade water quality through improper waste management techniques such as improperly applying manure to fields and through overgrazing or allowing animals direct access to streams. The part of pollution from rivers and streams that drain to Puget Sound that is specifically attributable to agricultural practices is not known (Puget Sound Water Quality Authority, 1986). However, several studies of commercial shellfish beds have strongly implicated animal-keeping practices on small noncommercial farms as contributing to bacterial contamination of shellfish beds (Puget Sound Water Quality Authority, 1986). Likewise, a statewide nonpoint source pollution assessment by Ecology indicated that agriculture, particularly animal keeping, had the greatest adverse effect on streams (Washington State Department of Ecology, 1989). Streams draining an agricultural subbasin of Newaukum Creek, a tributary to the Green River (fig 1), showed large concentrations of bacteria, suspended solids, and nutrients, compared with streams draining urban and forest subbasins of the Newaukum Creek drainage (Prych and Brenner, 1983).

Large concentrations of bacteria were also cited as problems in Tenmile and Fishtrap Creeks, tributaries to the Nooksack River (fig. 1), which drain agricultural areas with dairy cows (Whatcom County Conservation District, 1990 and Erickson, 1995). Fecal-coliform bacteria within tributaries to Fishtrap Creek were found to be as much as 140 times greater than the State of Washington water-quality standard of 100 organisms per 100 milliliters (Erickson, 1995).

Streams draining an agricultural area to Padilla Bay (fig. 6) in Skagit County were sampled for pesticides in a 2-year study by Mayer and Elkins (1990). Principal pesticides applied to farmlands in 1987 and 1988 were targeted for analysis. Of the 14 pesticides targeted, only dicamba and 2,4-D were found in water and sediment samples collected in the bay and three sloughs that enter the bay. Dicamba was found in all water samples after a major rain storm and was found in four bed sediment samples from sloughs. Mayer and Elkins (1990) concluded that no ecologically significant concentrations of any of the 14 targeted pesticides were found in water or bed sediments of the sloughs or Padilla Bay. A study by the Washington State Department of Ecology in 1992 also showed that pesticides that were used in a nearby agricultural area were not found in bed sediments from a small slough (Sullivan Slough) near the mouth of the Skagit River drainage (fig. 1) (Davis and Johnson, 1994). However, herbicides such as dicamba and 2,4-D have been found in the marine waters and bed sediments of Puget Sound (Puget Sound Water Quality Authority, 1990b).

Aquatic Biota

Many streams in the Puget Sound Basin have undergone significant changes in structure and function after settlement of the region and have trended toward simplification of stream channels and loss of habitat complexity (Bisson and others, 1992). The degree to which freshwater aquatic ecosystems in the Puget Sound Basin have been affected by these alterations is largely unquantified. Except for salmon, the aquatic ecosystem in the basin has been little studied. Salmon have been in general decline for the past 100 years (Washington State Department of Fish and Wildlife and others, 1993), and salmon may be a general indicator of the status of the aquatic ecosystem as a whole. However, salmon are anadromous and spend a large part of their life cycle in the ocean, and they are affected by influences from outside the basin. It is therefore difficult to clearly attribute the reasons for their decline to specific causes from within the basin or to directly infer the status of other species based on the status of salmon. Human effects on fish stocks and the difficulties in attributing specific reasons for the decline are described by Bisson and others (1992, p. 204): "Even where it can be shown that stocks are undergoing severe declines, it is usually impossible to determine with reasonable certainty the relative effects of habitat degradation, fishing pressure, and biotic interactions such as competition, predation, and disease. For most populations, declines have resulted from a combination of several factors, the relative importance of which may change from year to year."

Although definitive cause and effect relations are difficult to discern, the Washington State Department of Fish and Wildlife and others (1993) identified the relative importance of factors affecting salmon stocks (fig. 17). The factors most commonly cited as potential causes of salmon stock declines related to either degraded habitat (channel erosion and sedimentation, lack of woody debris, low pool abundance, loss of wetlands, and loss of riparian vegetation) or barriers to fish passage (dams and other barriers, agricultural dikes, and low summer flows). Water-quality effects on declining salmon stocks were noted much less frequently.

Water-quality influences on the freshwater aquatic ecosystem in the Puget Sound Basin have been little studied. The EPA's National Sediment Inventory data base, which contains a compilation of sediment and tissue data collected by various local, State, and Federal agencies from across the country (U.S. Environmental Protection Agency, 1994), includes only nine freshwater sites in the Puget Sound Basin where fish tissues were sampled for both trace elements and synthetic organic compounds and one site that was sampled for synthetic organic compounds alone. Ecology also sampled pesticides in fish tissue at one site in the Puget Sound Basin (Davis and Johnson, 1994). These analyses indicate that both trace elements and synthetic organic compounds were detected in fish tissue in the Puget Sound Basin. Concentrations of cadmium, copper, and lead in all fish-tissue samples exceeded nationwide mean concentrations (Schmitt and Brumbaugh, 1990) and concentrations of mercury, zinc, arsenic, and chromium in a few individual samples exceeded nationwide mean concentrations. Concentrations of synthetic organic compounds in fish tissue were below national averages and fish and wildlife protection guidelines for all sites except the Duwamish Waterway, which had elevated concentrations of alpha-BHC, aroclor-1254, total PCB, p-p'DDD, p-p'DDT, and total DDT; the Snohomish River, which had elevated levels of aroclor-1248; and Mercer Slough, which had elevated levels of p-p'DDD, aroclor-1260, and nonachlor. The concentrations of these metals and synthetic organic compounds in these fish tissue samples were all below levels attributed to lethal effects (Mayer and Ellersieck, 1986). However, the measured concentrations may not be below levels that may cause sublethal effects, which are less well understood.

Sublethal levels of many chemicals may not result in the direct death of an organism, but may produce immunologic, reproductive, or behavioral changes that indirectly result in reduced populations. Such behavioral changes include abnormal migration or movement, feeding behavior modifications, reduction in learning abilities, alterations in predator-prey interactions, and changes in social interactions (Rand and Petrocelli, 1985). Species of salmon and trout will alter their spawning and migration behavior in the presence of metals that are as low as one percent of their lethal concentrations (Sprague, 1964, and Saunders and Sprague, 1967). Trace elements and synthetic organic compounds at low concentrations are also suspected to cause disruption of the endocrine systems in aquatic organisms. Eighteen of 45 trace elements and synthetic organic compounds that are suspected to be endocrine disrupters (Colborn and others, 1993) were found in Puget Sound Basin fish tissue samples.

Ground Water

Known and suspected occurrences of ground-water contamination from sources at the land surface are numerous. The sources of ground-water contamination differ widely and include solid-waste landfills, spilled chemicals and petroleum fuels, wastes from mining and milling operations, waste-treatment lagoons, feedlots, large wood-waste disposal sites, and fertilizer and pesticide applications (Foxworthy, 1979; and U.S. Environmental Protection Agency, 1987). To mitigate sources of contamination of ground waters, Washington State agencies have worked since 1987 to develop ground-water-quality standards, regulate underground storage tanks, revise well construction standards, and develop solid and hazardous waste-management programs (Stratton, 1992). In 1992, an additional plan was developed to manage agricultural pesticides and fertilizers to protect ground water. Related issues cited by Stratton (1992) that pose some threats to ground-water quality include the uses of pesticides and fertilizers in urban and suburban areas, roadside right of ways, and small noncommercial farms. Disposal of unusable pesticides is considered a problem on farms (Meinz, 1987). An assessment of ground-water quality by Ecology concludes that most contamination of ground water in Washington State involves nonpoint sources (Washington State Department of Ecology, 1989).

The most comprehensive summary of ground-water-quality contamination statewide and in the Puget Sound Basin to date was compiled by Washington Toxics Coalition and Washington State University Cooperative Extension (Stewart and others, 1994). In this study, water-quality data from approximately 4,500 wells, sites, or well-dependent water systems in the Puget Sound region were compiled between 1985 and 1993. The most frequently detected groups of constituents in the region in decreasing order of frequency were nitrates, petroleum products, other synthetic organic compounds, trace elements, and pesticides (Stewart and others, 1994).

Nitrate is both the most prevalent and most frequently documented ground-water contaminant in the region (Stewart and others, 1994). Although some nitrate can be naturally present in ground water, national background concentrations are generally less than 3 mg/L (Madison and Brunett, 1985). Concentrations of nitrate exceeded 3 mg/L in about 7 percent of the water samples from nearly 2,000 public water-supply wells sampled in the Puget Sound Basin by the Washington State Department of Health (DOH). Using the last analysis available for each individual well (as opposed to well systems), less than one percent of the sampled waters exceeded the EPA maximum contaminant level (MCL) of 10 mg/L. Recently compiled information indicates that the largest concentrations of nitrates in the Puget Sound Basin are associated with shallow wells in unconfined coarse-grained glacial aquifers (Tesoriero and Voss, in press) where nitrate from chemical fertilizer and manure and other sources might easily reach the water table. Large concentrations of nitrates were observed in the Puget Sound Basin and in other regions of Washington State in the ground water of urban areas with highly permeable soils that allow septic-tank effluent to rapidly infiltrate to the ground-water system (Lum and Turney, 1982). In another statewide compilation, areas of large nitrate concentrations (exceeding 5 mg/L) are shown to exist in ground water underlying urban-suburban land cover, particularly in parts of Thurston, Pierce, King, and Snohomish Counties (Stewart and others, 1994).

Nitrate concentrations commonly exceed the 10 mg/L MCL, in aquifers underlying agricultural areas of Whatcom County in the northern part of the Puget Sound Basin (fig. 1) (Stewart and others, 1994). Ecology sampled water from 27 shallow wells in a 6.5 mi^2 area of Whatcom County in 1988 (Erickson and Norton, 1990). The average nitrate concentration in water samples from these 27 wells was 6.7 mg/L as nitrogen, and the average nitrate concentration from a set of resampled water from 11 wells was 11.0 mg/L (Erickson and Norton, 1990). Of the samples from the shallow 27 wells, 9 exceeded the MCL of 10 mg/L for nitrate. A broad sampling of water from wells in a 625-mi^2 agricultural area of Whatcom County by the USGS from 1990 to 1992 found about 15 percent of the well water samples had nitrate concentrations above the MCL (S.E. Cox, U.S. Geological Survey, written commun., August 1995). The largest concentrations of nitrate occurred in a shallow aquifer composed of mostly coarse-grained glacial sediments. Locally, large concentrations of nitrate have been found north of the United States-Canada border in the same aquifer underlying the agricultural area of Whatcom County (Liebscher and others, 1992). In the Puget Sound Basin, ground water that exceeds the nitrate MCL is found mainly in Whatcom County and at scattered locations in Island, Thurston, King, and Snohomish Counties (fig. 1), according to the data compiled by Stewart and others (1994).

A comprehensive sampling of drinking water supplies by DOH indicates the occurrence and distribution of volatile organic compounds (VOCs) in ground water. Through the early 1990's, several hundred wells or well systems used for drinking water have been tested statewide for VOCs following the establishment of MCLs for 18 VOCs in 1992 (Stewart and others, 1994). Stewart and others (1994) define petroleum products and other synthetic organic compounds within the class of compounds analytically defined as VOCs. Volatile organic compounds associated with petroleum products include benzene, toluene, xylene, and ethyl benzene. Volatile organic compounds that are called "other synthetic organic compounds" by Stewart and others (1994) include many VOCs commonly used as solvents, industrial degreasers, petrochemical by-products, and chemicals for industrial manufacturing. The most frequent detections of VOCs associated with petroleum products and synthetic organic compounds were in ground water in eastern Snohomish, King, and Pierce Counties, generally from Tacoma to Everett (fig. 1), the most urbanized part of the Puget Sound Basin (Stewart and others, 1994).

In the Puget Sound Basin, volatile organic compounds were detected in about 3.4 percent of wells sampled from 1988 to 1994 by DOH. The well-water systems sampled by DOH for VOCs tend to be deeper wells used for the public drinking water supply. Of the well water with detectable concentrations of volatile organic compounds, most had 1 to 2 detectable concentrations of VOCs per sample from a total of more than 50 VOCs analyzed. Trihalomethanes, which can result from chlorination of water in the presence of certain organic chemicals, were not included in the data analysis. The most commonly detected VOC in the basin was tetrachloroethylene, which is primarily used as a solvent in dry cleaning, and to a lesser extent as a degreasing solvent in metal industries (U.S. Environmental Protection Agency, 1980). Data compiled nationwide by Plumb and Pitchford (1985) indicate that tetrachloroethylene ranks first in frequency of occurrence in ground water at hazardous waste disposal sites.

Unlined sanitary landfills and leaking underground storage tanks (Sumioka, 1995) can cause volatile organic compounds and other petroleum-related compounds to spread as an underground plume that may contaminate soils and reach the water table. On a regional scale, such as the size of the Puget Sound Basin, these facilities function as point sources of contamination. Seventy percent of all underground storage tanks are located at commercial facilities (Washington State Department of Ecology, 1994). According to Ecology, many landfills were not constructed under current liner design requirements, and consequently many of the landfills are producing uncontrolled leachate that can contaminate ground water. Numerous site-specific studies have documented plumes of organic and other contaminants migrating various distances from landfill sources.

The overall degree of ambient ground-water contamination by pesticides is difficult to assess from existing data sources. The most comprehensive pesticide study in the region involved the sampling of approximately 1,300 public water-supply wells and analyses of 27 pesticides in the summer of 1994 by DOH. The wells sampled were divided into random and high risk groups. The high risk group of wells is generally defined by DOH as those wells with a history of intensive land use in the vicinity, water-quality problems, or relatively shallow depths (Washington State Department of Health, 1995). Random wells were selected by a computerized process. The sampling was done in three rounds each with a somewhat different objective and well selection process. Pesticides were detected in about 4 percent of the random wells and 14 percent of the high risk wells in the Puget Sound Basin (Ryker and Williamson, 1996), but in only one well was a pesticide concentration (pentachlorophenol) above the EPA MCL. The pesticides detected most commonly in the region's ground-water-supply wells were atrazine, simazine and dicamba. Preliminary projections by the DOH assert that pesticide contamination of drinking water in the region presents a low public health risk. This projection is based on a low incidence of pesticide detections, small concentrations of detected pesticides, and the limited variety of pesticide compounds detected (Washington State Department of Health, 1995).

Pesticide use in urban and suburban areas is large and varied and is likely to increase as the population increases in the Puget Sound Basin. There has been little monitoring of ambient pesticide concentrations in the shallow ground water of urban areas to determine occurrence and distribution of pesticides. However, in specific areas near waste disposal sites, pesticides are frequently detected. For example, of 239 major waste cleanup sites statewide, pesticides have been detected in 28 percent of the sites (Stewart and others, 1994).

Agricultural use of pesticides is probably stable or declining in the Puget Sound Basin as urbanization increases (Puget Sound Water Quality Authority, 1990a). Some targeted-pesticide studies have been conducted in agricultural areas of the basin, and pesticides have been found in ground water. Ground water was sampled for pesticides from 27 wells located in Whatcom County in 1988 (Erickson and Norton, 1990). Of 46 pesticides targeted for analysis, only 5 were found at detectable concentrations (Erickson and Norton, 1990). Two of the five pesticides detected were dibromochloropropane (DBCP) and ethylene dibromide (EDB), which were commonly used as soil fumigants prior to their suspension by the EPA. Other pesticides found at detectable concentrations were carbofuran, 1,2-dichloropropane, and prometon. Pesticides found in ground water of the agricultural area in Whatcom County were compiled by S.E. Cox (U.S. Geological Survey, written commun., May 1995). The compilation by Cox revealed that 16 individual pesticide compounds were detected in well water by different investigators between 1985 and 1993. Four of the pesticides detected were used as soil fumigants, and 7 of the 16 pesticides had concentrations exceeding the MCL or health advisory of the EPA. The seven pesticides that exceeded the MCL or health advisory are (in the order of frequency) EDB, 1,2-dichloropropane, diazinon, DBCP, simazine, atrazine, and endosulfan. The last four pesticides listed had only one detection each. When State agencies and counties monitored ground water in the 1980's, they also detected EDB in ground waters of Skagit and Thurston Counties (fig. 1) (Stewart and others, 1994). Communities located in Whatcom, Skagit, Snohomish, and Thurston Counties requested in the early 1990's that DOH test drinking water for EDB and DBCP. As a result, drinking water from about 160 water-supply wells was tested, but showed no detectable concentrations of EDB or DBCP (Ginny Stern, Washington State Department of Health, written commun., June 1995).

SUMMARY

Existing information indicates that the quality of surface and ground water in the Puget Sound Basin is generally good. The natural background qaulity of surface and ground water is generally cool, clear, chemically dilute, and suitable to support most beneficial uses. However, streams fed by glacial meltwater are often turbid and sediment laden for long periods in the mid to late summer, and natural concentrations of iron and manganese in ground water commonly exceed secondary drinking water-quality standards. Natural concentrations of arsenic in ground water also exceed the primary drinking-water standard in a few isolated locations.

Land use in the Puget Sound Basin differs greatly between the forested upper watersheds and the urban and agricultural lower watersheds, and the water-quality issues in these parts of the basin differ accordingly. The chemical quality of most streams and lakes in the upper watershed is suitable to support fish and aquatic life as well as other uses. However, the hydrology, channel morphology, water temperature, and biologic integrity of many of these streams have been degraded to varying degrees by logging. Many of the salmon stocks that spawn in these upper watershed streams are in decline, and the effects of logging on fish habitat is an issue of heightened concern within the basin.

In the developed lowlands, most contaminant point sources discharge directly to Puget Sound, leaving nonpoint sources as the primary focus of concern for the basin's freshwater quality. In lowland streams, water-quality standards are most frequently not met for fecal-coliform bacteria, stream temperature, and occasionally disolved oxygen. Water-quality standards for nutrients and toxic contaminants such as trace elements and synthetic organic compounds are met for most streams. However, the loading of nutrients and toxic contaminants are of concern to receiving waters such as Puget Sound and the region's many lakes. Contaminants associated with sediment are of particular concern in that most sediment settles permanently within Puget Sound and associated contaminants affect the marine benthic ecosystem. Residuals of those chlorinated pesticides that have been banned by EPA are still found in the bed sediment of streams draining urban and agricultural lands.

Pesticides that are in current use have also been detected in the water of many of these same streams. The concentration of these pesticides in bed sediment and stream water are generally lower than existing criteria. However, sublethal effects of these pesticides on the aquatic ecosystem are of growing concern.

Ground water supplies about 40 percent of the drinking water in the Puget Sound Basin and is the principal source of drinking water in most rural and some suburban areas. The quality of ground water used for drinking water is best documented for public water-supply wells, and this water, with few exceptions, meets drinking-water-quality standards. Nitrate is the most commonly detected ground-water contaminant. About 7 percent of public water-supply wells have elevated nitrate concentrations (greater than 3 mg/L) and less than 1 percent exceed the 10 mg/L drinking water standard. Pesticides have been detected in about 4 percent of the public water-supply wells sampled, and volatile organic compounds (VOCs) have been detected in 3.4 percent of the public water-supply wells sampled. With the exception of pentachlorophenol in one well, none of these detections exceeded drinking-water standards. Elevated nitrate concentrations and detections of pesticides and VOCs occurred most frequently in the shallow unconfined glacial outwash aquifers, where they are overlain by agricultural and urban land uses.

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