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Summary of the Puget-Willamette Lowland Regional Aquifer-System Analysis, Washington, Oregon, and British Columbia

By J.J. Vaccaro, D.G. Woodward, M.W. Gannett, M.A. Jones, C.A. Collins, R.R. Caldwell, and A.J. Hansen

A Contribution of the Regional Aquifer-System Analysis Program

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1,233.50	cubic meter
cubic mile (mi^3)	4.168	cubic kilometer
inch per year (in/yr)	2.54	centimeter per year
foot per foot (ft/ft)	1.0	meter per meter
foot per mile (ft/mi)	0.18943	meter per kilometer
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Temperature: To correct temperature given in this report in degrees Fahrenheit (°F) to degrees Celsius (°C), use the following equation: °C = 5/9(°F-32)

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 Sea Level Datum of 1929.

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ABSTRACT

The Puget-Willamette Lowland regional aquifer-system analysis included the study of the regional aquifer systems underlying western Washington, western Oregon, and a small part of southwestern British Columbia, Canada, for a total study area of about 23,300 square miles. Two major aquifer systems are contained in the study area—the Puget Sound aquifer system located in western Washington and southwestern British Columbia, Canada, and the Willamette Lowland aquifer system located in western Oregon and southwestern Washington. The Puget Sound aquifer system study area includes about 17,600 square miles, of which the aquifer system underlies 7,300 square miles; the Willamette Lowland aquifer system study area includes about 5,700 square miles, of which the aquifer system underlies about 3,660 square miles. The aquifer systems provide water for public supply, industrial, and agricultural use. About 984,840 acre-feet, or 1,291 cubic feet per second, was pumped from the aquifer systems during 1990.

The Puget-Willamette Lowland is a discontinuous valley that is a forearc basin formed by the convergence of tectonic plates. The lowland contains two Neocene-age sedimentary basins separated by bedrock uplands. The sediments that compose the Puget Sound aquifer system in the north consist of glacial and interglacial Pleistocene deposits and in places, large thicknesses of Holocene alluvial deposits underlying broad, flat alluvial valleys. The aquifer system is as much as 3,300 feet thick. The rocks that compose the Willamette Lowland aquifer system on the south consist of Miocene basalts, Pliocene-to-Pleistocene basin-fill deposits, Pleistocene glacial-outburst flood deposits, small quantities of glacial outwash deposits, and Holocene alluvial deposits. The aquifer system is as much as 2,000 feet thick.

Bedrock uplands separate the Puget Sound Lowland into three major structural basins, and basalt uplands separate the Willamette Lowland into four distinct structural basins. The lateral and basal boundaries of the Puget Sound aquifer system are composed of low permeability Tertiary and older marine and non-marine sedimentary, volcanic, volcaniclastic, and metamorphic rock units. The rock units forming the boundaries of the Willamette Lowland aquifer system are composed of older Tertiary marine sediments and volcanics and non-marine volcanics. For both aquifer systems, these units are collectively named the basement confining unit. About 1,315 cubic miles of aquifer materials overlie this unit in the Puget Sound Lowland. At least 265 cubic miles of aquifer materials overlie this unit in the Willamette Lowland.

The Puget Sound aquifer system was divided into six regional hydrogeologic units—the surficial semiconfining unit, the Fraser aquifer, the confining unit, the Puget aquifer, alluvial aquifers (nine of which were named and delineated), and the basement confining unit. The aquifers generally consist of coarse-grained glacial outwash deposits, proglacial deposits, and alluvial deposits; the semiconfining and confining units generally consist of fine-grained glacial till, glaciomarine deposits, and interglacial lacustrine deposits. Variations to these overall lithologic patterns exist throughout the Puget Sound Lowland.

The Willamette Lowland aquifer system was divided into five regional hydrogeologic units—the Willamette silt unit, the Willamette aquifer, the Willamette confining unit, the Columbia River basalt aquifer, and the basement confining unit. The Willamette aquifer consists of coarse-grained basin-fill deposits, outburst-flood deposits, and alluvial deposits. Except for the northern part of the Willamette Lowland, the thickest section of coarse-grained deposits generally are found in extensive alluvial

fans emanating from the Cascade Range on the east or in the modern flood plain of the Willamette River. In the northern part, the coarse-grained deposits predominantly consist of Columbia River sediments and outburst-flood deposits. The Columbia River basalt aquifer consists of accordantly layered basalt flows of the Columbia River Basalt Group. The silt unit is principally composed of the Willamette Silt, the fine-grained facies of the outburst-flood deposits. The confining unit is composed of fine-grained basin-fill deposits which generally correspond to the lower section of the basin-fill sediments, but in the Tualatin Basin also includes the surficial outburst-flood deposits.

The aquifers composed of unconsolidated deposits locally have average hydraulic conductivities that range from 5 to 1,000 feet per day. Generally, the large values are associated with Holocene alluvial deposits and gravel-dominated glacial outwash and alluvial fan deposits. The small values generally are associated with silty sand to sandy deposits (outwash and fluvial deposits). The basalt aquifer generally has conductivities that range from 0.01 to 100 feet per day, and average about 1 foot per day.

Estimated mean annual recharge to the Puget Sound and Willamette Lowland aquifer systems is about 27.4 inches (14,510 cubic feet per second) and 19.3 inches (5,463 cubic feet per second), respectively. These values are about 52 and 41 percent of the mean annual precipitation falling on each system, respectively.

Topography, configuration of the basement confining unit, aquifer geometry, and discharge locations (saltwater boundaries and streams) all provide hydrologic control on the ground-water flow systems. Ground water in the unconsolidated deposits generally occurs under unconfined to semiconfined conditions. However, in the Puget aquifer and the deeper parts of the Willamette aquifer, ground water also occurs under confined conditions. In the Columbia River basalt aquifer, ground water occurs under unconfined conditions in its outcrop area and becomes increasingly confined with depth.

For both aquifer systems, ground water moves from topographic highs to topographic lows which generally are either streams or saltwater bodies. A large part of the recharge moves along short flow paths in the upper part of the systems and is discharged locally. Water-level maps indicate that horizontal hydraulic gradients range from 0.0009 to 0.01 foot per foot. The smaller gradients typically occur in areas of relatively flat topography where the aquifer materials are coarse-grained and are not overlain by a fine-grained unit; the larger gradients typically occur in areas of large topographic relief. The lengths of ground-water flow paths range from as short as 1,000 feet to as long as 40 miles. For the Puget Sound aquifer system, most flow paths range from 2 to 7 miles in length, and maximum lengths are about 20 miles. For the Willamette Lowland aquifer system, most flow paths range from 3 to 15 miles in length and maximum lengths are about 40 miles. No flow paths extend the length of either system, principally due to structural control or saltwater-boundary control, and secondarily due to the control of surface-water bodies (discharge locations along streams). Connected subregional flow systems exist in each of the four basins in the Willamette Lowland, whereas connected subregional flow systems exist only in one basin and part of a second basin in the Puget Sound Lowland. The remaining areas are typified by isolated small-scale flow systems.

Mean annual unit recharge to the low-lying parts of each aquifer system ranges from 0.20 to 1.5 cubic feet per second per square mile. Unit discharge within local flow systems ranges from 0.25 to 1.25 cubic feet per second per square mile and supports streamflow for much of the year. The remaining recharge discharges either as evapotranspiration or as seepage to the regional drains—saltwater bodies and major rivers of the Puget Sound aquifer system, and the Columbia and Willamette Rivers of the Willamette Lowland aquifer system. The regional unit discharge is much less than the local discharge and ranges from about 0.10 to 0.25 cubic feet per second per square mile.

The ground water contained in the aquifer systems generally is of good quality and is suitable for most uses. Except for the deepest parts of the flow systems, the water generally is homogenous with respect to common chemical characteristics. The primary water-quality problems for the Puget Sound aquifer system are locally large concentrations of nitrate that appear to be related to land-use activities, and large chloride concentrations due to seawater intrusion. For the Willamette Lowland aquifer system, the primary problem is locally occurring large concentrations of chloride that are related to the upconing of connate water contained in marine sediments of the basement confining unit. This problem is most prevalent where the Willamette confining unit is thin and adjacent to major faults because the saline connate water is confined with a dominant upward flow component.

INTRODUCTION

The U.S. Geological Survey initiated the Regional Aquifer-System Analysis (RASA) program in 1978 in response to congressional concerns about the availability and quality of the Nation's ground water. The purpose of the RASA program is to aid in the effective management of important ground-water resources by providing information on the hydrogeology of regional aquifer systems, as well as analytical capabilities necessary to assess management alternatives (Sun, 1986). The two regional aquifer systems contained in Puget-Willamette Lowland were chosen to be studied in this program (Sun, 1986; Vaccaro, 1992).

In order to meet the overall RASA program goals, the major objectives of the Puget-Willamette Lowland study were to: (1) describe the geologic framework of the regional aquifer systems; (2) describe the hydrogeologic characteristics of the regional aquifer systems; (3) describe the regional ground-water flow systems and their major hydrologic controls; (4) estimate the water budgets for selected areas and use this information to describe the regional water budget; and (5) provide for a synthesis of knowledge of the two regional ground-water flow systems. A detailed description of the purpose and plan of the study is given by Vaccaro (1992).

The Puget-Willamette Lowland is located in western Washington, western Oregon, and a small part of southwestern British Columbia, Canada (fig. 1). The study area is contained within a structural basin that extends from near the Fraser River, British Columbia, Canada at about 49 degrees, 15 minutes north latitude, to just south of Cottage Grove, Oreg., at about 44 degrees north latitude. The Puget-Willamette Lowland study area includes about 23,290 mi^2.

The Puget-Willamette Lowland comprises two major Neocene sedimentary basins separated by bedrock uplands. The basins compose two distinct areas, the Puget Sound Lowland and the Willamette Lowland. The Puget Sound Lowland in Washington and British Columbia, Canada encompasses about 17,616 mi^2, about 2,556 mi^2 of which is salt water, and the Willamette Lowland in Oregon and Washington encompasses about 5,680 mi^2. The Puget Sound Lowland includes most of the Puget Sound drainage, which drains part of the Cascade Range and the Olympic Mountains, a small part of the Fraser River drainage in Washington and British Columbia, Canada, and small areas both south and southwest of the Puget Sound drainage. The Willamette Lowland in Oregon and Washington includes the low-lying parts of the Willamette River drainage, which drains the Cascade Range and Coast Mountains in Oregon, and a small part (635 mi^2) of Clark County, Wash.

The Puget Sound Lowland and the Willamette Lowland contain two hydrologically and geologically distinct aquifer systems. The aquifer system in the Puget Sound Lowland is named the Puget Sound aquifer system, and the system in the Willamette Lowland is named the Willamette Lowland aquifer system. The lateral extent of the principal aquifer units in the Puget Sound Lowland is defined by the area underlain by glacial and nonglacial Quaternary sediments; in the Willamette Lowland the extent is defined by the area underlain by Holocene alluvial deposits, Pliocene-to-Pleistocene basin-fill sediments and volcanics, and upper Tertiary volcanics.

About 70 percent of the population of Washington and Oregon reside in the study area, mainly in the metropolitan areas of Bellingham, Everett, Seattle and vicinity, Tacoma, and Olympia in the Puget Sound Lowland; and Vancouver, Portland and vicinity, Salem, and Eugene in the Willamette Lowland. Additionally, about 75 percent of the population of British Columbia, Canada reside in the Canadian part of the study area. The burgeoning population is increasing the demand for the available water. In some areas, available water supplies are already fully appropriated, and supplies are limited due to contamination from anthropogenic sources and to saltwater intrusion from the Puget Sound in the Puget Sound Lowland, and by brackish ground water in the Willamette Lowland.

The results of the Puget-Willamette Lowland study are presented in the U.S. Geological Survey Professional Paper 1424, Chapters A-D. Chapter A (Gannett and Caldwell, in press) presents the geologic framework for the Willamette Lowland aquifer system and Chapter C (Jones, in press) presents the geologic framework for the Puget Sound aquifer system. The hydrogeologic framework for the Puget Sound and the Willamette Lowland aquifer systems are presented in Chapters D (Vaccaro and others, in press) and Chapter B (Woodward and others, in press), respectively. Previous investigations covering the geology and hydrology of the Puget-Willamette Lowland study area are thoroughly documented in Chapters A through D and in two bibliographies (one for each area) developed during this study (Jones, 1991; Morgan and Weatherby, 1992). This report summarizes the results of the study.

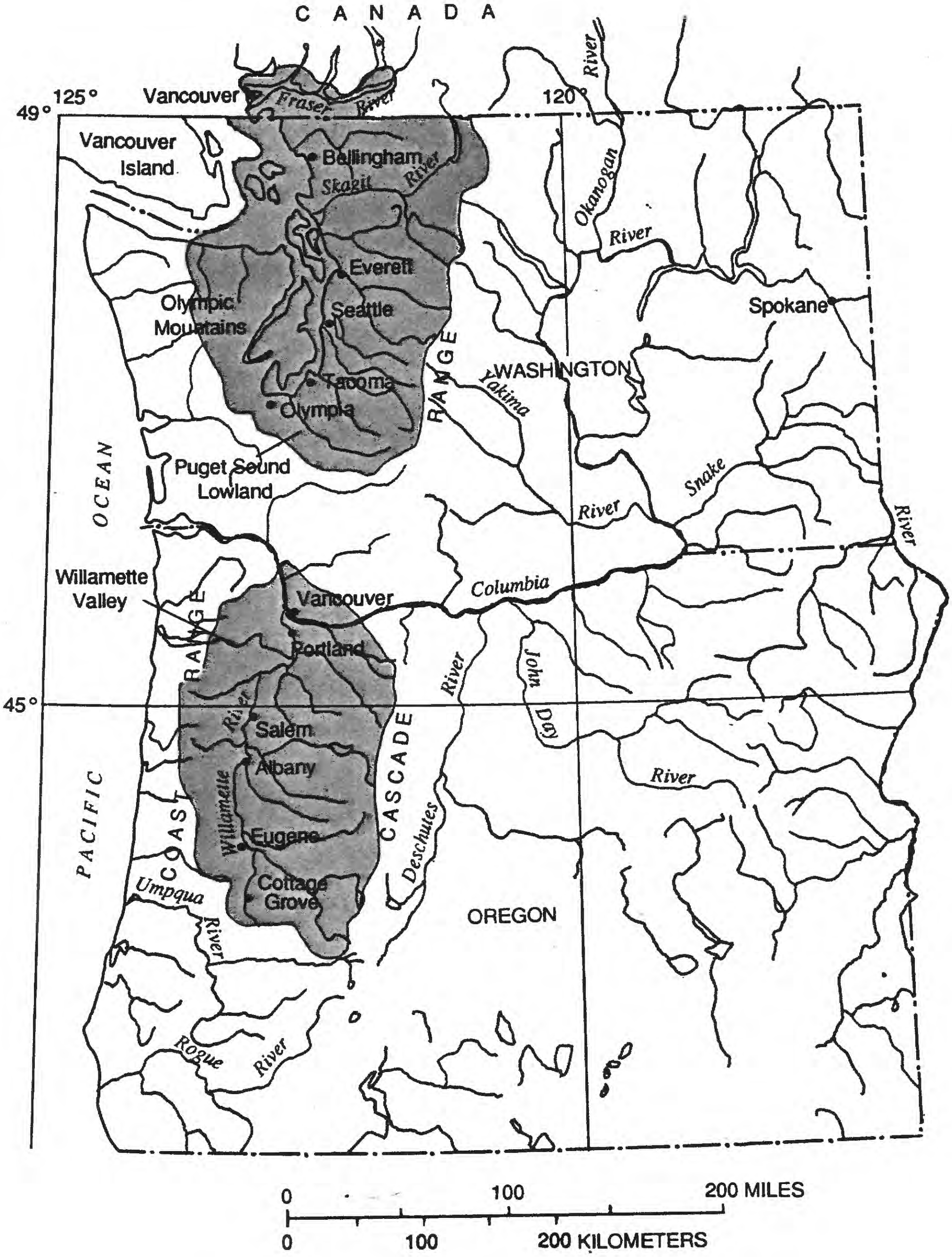


Figure 1.--Location of the study area.

In this report, the regional physical and geologic setting for the Puget-Willamette Lowland RASA is first described. An overview of the aquifer systems present in each area and their differences is then presented. Because this RASA study includes two distinct aquifer systems, the remaining parts of this summary are divided into two sections—one for the Puget Sound aquifer system and the other for the Willamette Lowland aquifer system. For each aquifer system, a summary of the geology and the hydrogeologic units is first presented. Ranges in hydraulic conductivity of the hydrogeologic units are next presented. Hydraulic conductivity is presented because it is perhaps the most important hydraulic characteristic for describing ground-water flow. The hydraulic conductivity of a hydrogeologic unit characterizes the unit as either an aquifer or a semiconfining-to-confining unit, and the distribution of hydraulic conductivity controls the flow of water within and between units. Next, estimates of ground-water recharge are described. Generalized areal distributions of the estimates of mean annual recharge are presented for both aquifer systems because recharge is important for determining ground-water availability, and for describing the potential for contaminant transport. Ground-water movement is then described. Last, water use and water-quality characteristics are summarized. These summarized results of this study are presented in more detail in U.S. Geological Survey Professional Paper 1424, Chapters A through D.

REGIONAL SETTING

Physical Setting

The Puget-Willamette Lowland is bordered by the Fraser River and the international boundary on the north, the Cascade Range on the east, and the Coast Range and Olympic Mountains on the west. North of the Olympic Mountains, the western boundary is defined by the Canada-Washington State boundary located in the waters south and east of Vancouver Island, British Columbia. The southern boundary is a line of foothills where the Coast and Cascade Ranges merge (fig. 1).

The southern boundary of the Puget Sound Lowland is approximately defined by the extent of the Pleistocene glaciation, which is characterized by a series of low hills near the divide between the Puget Sound drainage and the Chehalis River basins; however, it extends beyond the Puget Sound drainage to include all or parts of several small drainages (fig. 2a).

The northern boundary of the Willamette Lowland is located along the Lewis River in Clark County, Wash., and is defined by an outcrop of the Columbia River Basalt Group that extends northward along the Columbia River from north of Portland, Oreg. to near Woodland, Wash. (fig. 2b). This northern boundary generally is defined where the Coast and Cascade Ranges merge.

The Puget Sound Lowland extends over 200 mi in a north-south direction, and the low-lying part ranges from 15 to 80 mi in width and averages about 40 mi. The Willamette Lowland extends over about 145 mi in the north-south direction and the valley floor ranges between 10 to 15 mi in width in the southern part and widens gradually northward to a maximum of about 45 mi in the northern part.

Altitudes of the valley floors or lowlands range from sea level to about 500 ft. The foothills or uplands of both areas have altitudes ranging from 500 to about 1,500 ft. The altitude of the crest of the Cascade Range averages 7,500 ft on the north to about 4,500 ft on the south, but a series of stratovolcanoes in the Cascade Range rise from 8,000 to 14,000 ft above sea level. The altitude of the Olympic Mountains in the northwest part of the Puget-Willamette Lowland averages about 3,000 ft, but some peaks are 6,000 to 7,000 ft. The rugged Coast Range in the southwest has lower altitudes, averaging less than 2,000 ft, but altitudes are as high as 4,100 ft west of Corvallis, Oreg.

In the Puget Sound Lowland, the lowlands are alluvial river valleys separating glacial outwash and till plains. In the Willamette Lowland, the lowlands are valley floors separated by terraces and basalt hills. The lowlands are separated from the bordering mountains by uplands with rolling hills and terraces. The transition from the uplands to the mountains generally is abrupt, except near the southern boundary of each subarea.

Figure 2a.--Major physiographic features of the Puget Sound Lowland.

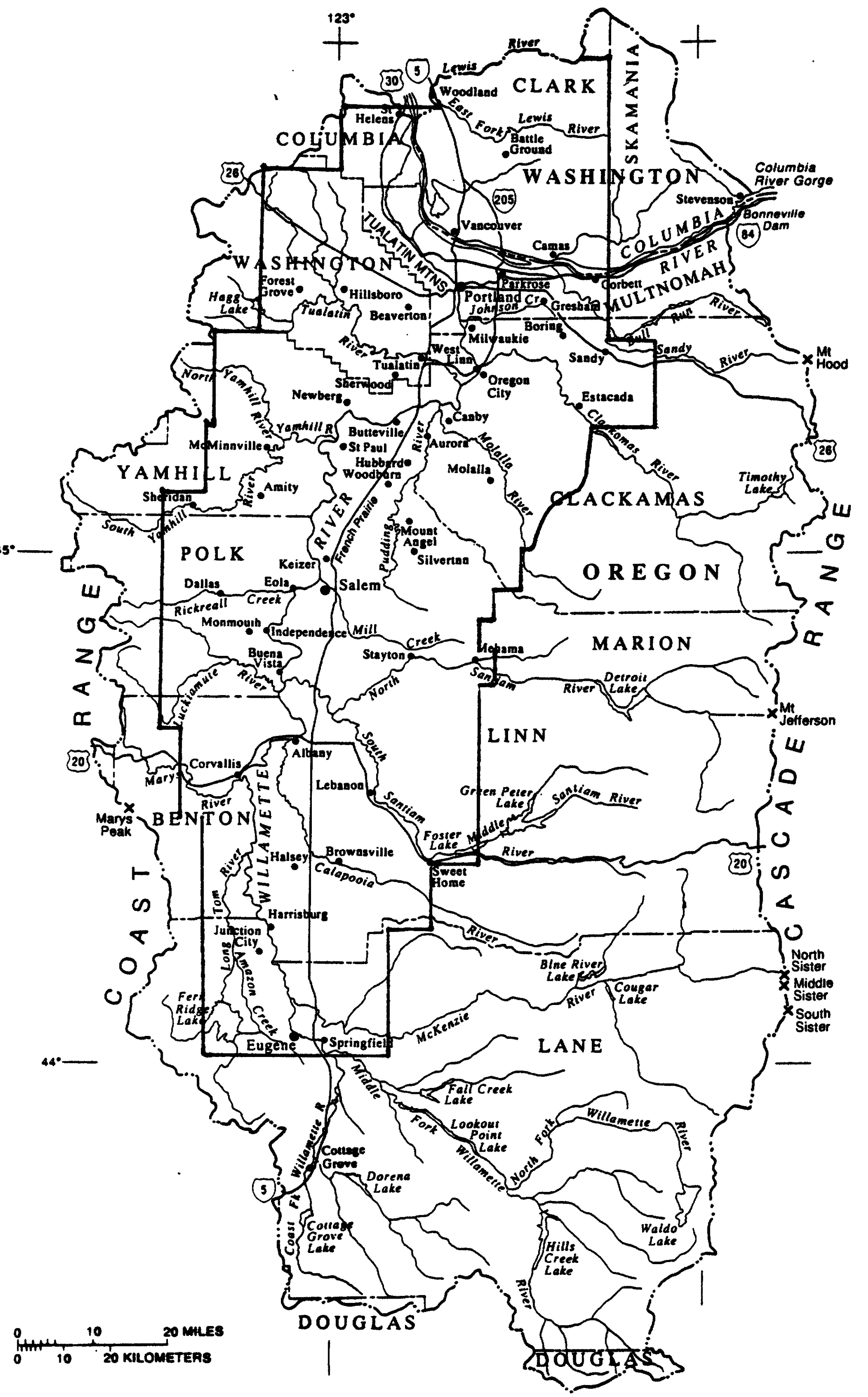


Figure 2b.—Major physiographic features of the Willamette Lowland.

Bedrock uplands separate the low-lying parts of the Puget Sound Lowland into three distinct subareas—the southern Puget Sound Lowland, north-central Puget Sound Lowland, and the Fraser-Whatcom Basin (shown on fig. 6). Additionally, several structural basins are present within the first two basins.

The Willamette Lowland topography is interrupted in places by narrow, north- and northwest-trending basalt uplands and by numerous irregularly shaped, low volcanic hills consisting of basalt lava flows. These volcanic hills and ridges range in altitude from a few hundred feet to as much as 1,200 ft. The geologic structures, expressed as the basalt uplands, present in the Willamette Lowland divide the valley into four distinct structural and topographic basins—the southern Willamette Valley, the central Willamette Valley, the Tualatin Basin, and the Portland Basin (shown on fig. 11).

The Puget-Willamette Lowland has a mid-latitude humid Pacific Coast marine climate due to the easterly moving air masses from the Pacific Ocean. The adjacent mountains provide protection from the southerly moving Canadian cold-air masses and from the Pacific Ocean winter storms. As a result, both summer and winter temperatures are moderated; there is a distinct winter precipitation season and a summer dry season; and altitude and location have a large influence on the distribution of precipitation and on temperature.

Within the lowlands of the Puget Sound Lowland, precipitation ranges from 16 to 19 in/yr in the "rain shadow" of the Olympic Mountains to 53 in/yr near Olympia, Wash. Within the lowlands of the Willamette Lowland, precipitation ranges from 37 in/yr near Portland, Oreg. to 55 in/yr near Sandy, Oreg.; much of the lowlands receive 40 in/yr. Typical temporal distributions of water-year precipitation at three weather sites within the lowlands are shown on figure 3.

In the Cascade and Olympic foothills of the Puget Sound Lowland, the annual precipitation ranges from 45 to 60 in/yr, with the larger values being more typical of the Olympic Mountains. Correspondingly, the annual precipitation in the Coast and Cascade foothills in the Willamette Lowland ranges from about 50 to 60 in/yr. Throughout the mountains, at altitudes between about 1,500 and 2,500 ft, precipitation ranges from about 60 to more than 100 in/yr; at higher altitudes, precipitation generally is more than 90 in/yr. Estimated mean annual precipitation for the Puget Sound Lowland study area is 73.8 in. or 81,610 ft^3/s; and mean annual precipitation in the Willamette Lowland study area is 51.1 in. or 21,350 ft^3/s. About 53.2 in/yr or 28,170 ft^3/s of the precipitation in the Puget Sound Lowland falls on the aquifer system, and 46.6 in/yr or 13,187 ft^3/s of precipitation falls on the Willamette Lowland aquifer system.

About 80 percent of the precipitation falls during the winter season of October through March and is rain below about 1,000 ft, both rain and snow at altitudes between about 1,000 to 1,500 ft, and snow at higher altitudes. The summers are relatively dry; average July precipitation in the lowlands generally is less than 0.75 in.

Mean annual maximum air temperatures range from about 60 °F in the lowlands to about 47 °F in the mountains, and mean annual minimum temperatures range from about 40 °F in the lowlands, to about 31 °F in the mountains. Generally, in the lowlands, summer temperatures range from 60 to 90 °F and winter temperatures range from 30 to 50 °F.

In the Puget Sound Lowland, annual surface-water runoff for the Puget Sound drainage (about 13,355 mi^2) averages about 46,000 ft^3/s (45 in/yr). Runoff for the Willamette River drainage is quite similar and averages about 32,000 ft^3/s (40 in/yr) from about 11,100 mi^2. Runoff in selected basins in both subareas generally ranges from about 35 to 80 in/yr.

Excluding Canada, the Puget Sound Lowland contains 20 major drainages or hydrologic units and parts of two other hydrologic units, and the Willamette Lowland drainage contains 15 units and part of another hydrologic unit (U.S. Geological Survey, 1976a,b). In many areas, the surface-water and ground-water drainage basin boundaries are equivalent because of bedrock configuration and topography. The runoff in parts of the Puget Sound Lowland is controlled by the presence of 386 glaciers, which cover about 116 mi^2 and contain about 13 million acre-ft of water. The glaciers help to provide consistent summer flows, especially in the Skagit, Puyallup, and Nisqually Rivers. Similarly, glaciers in the Willamette River drainage provide additional flow to the McKenzie, Santiam, and Clackamas Rivers.

Numerous natural lakes are present in the Puget Sound Lowland, while lakes in the Willamette Lowland are few and generally man-made. About 22 major reservoirs in the Puget Sound Lowland store about 3,100,000 acre-ft and 20 major reservoirs and lakes in the Willamette Lowland have a storage capacity of about 3,400,000 acre-ft.

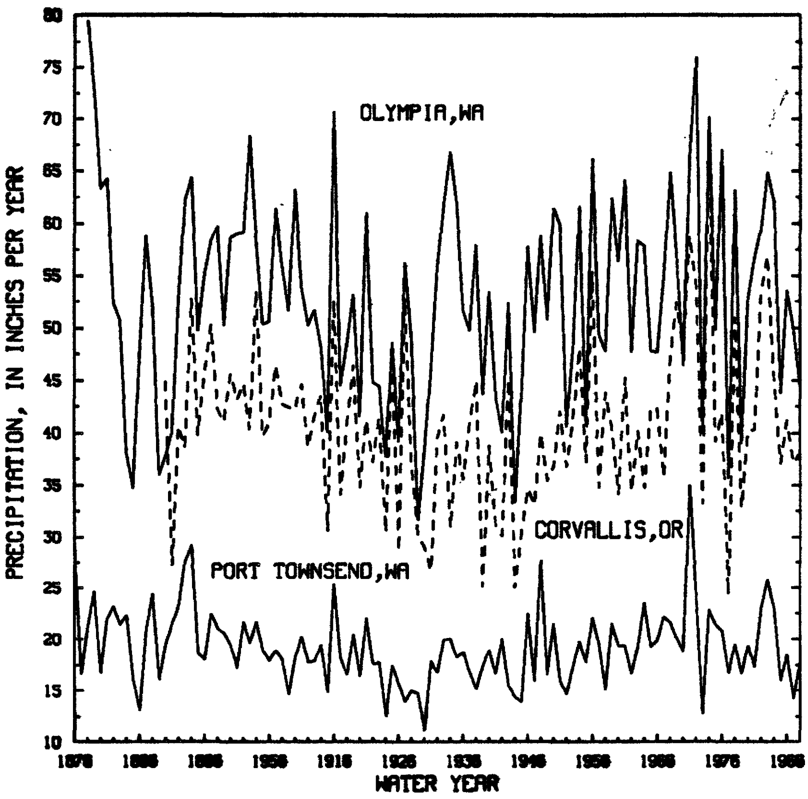


Figure 3.--Temporal distribution of water-year precipitation at thre weather sites in the lowlands of the Puget-Willamette Lowland.

Geologic Setting

The regional geologic evolution and setting of the Puget-Willamette Lowland is largely a function of plate tectonics. The western part of the Pacific Northwest is an active continental margin where the North American continental plate has been converging with the oceanic plates of the north Pacific Basin throughout much of Cenozoic time (Atwater, 1970; Engebretson and others, 1985). The subduction of the ocean plates has been accompanied by rifting, extension, and volcanism. The regional topography and geology are the products of tectonic convergence of the plates.

The Cascade Range is an active magmatic arc formed by the continuing subduction of the Juan De Fuca plate beneath the North American plate (fig. 4). Most of the western edge of the Cascade Range is bounded at depth by marine sedimentary and volcanic complexes of Eocene thorough Miocene age that have, in part, been accreted to the North American plate (Cady, 1975; Adams, 1984; and Snavely, 1988). The Olympic Mountains, for example, are part of an exotic terrane, a remnant of the upper part of the descending oceanic plate that was scraped off the subducting plate, became attached to the leading edge of the North American Plate, and then was uplifted; the mountains lie on the trench-slope break and are part of the trench system (fig. 4). The Puget-Willamette Lowland is a discontinuous valley that is a forearc basin which commonly lies between the trench and magmatic arc (Dickinson, 1976) (fig. 4). The Coast Range in the Willamette Lowland is the end product of the regional uplift of the forearc basin and, similar to the Olympics, consists of large thicknesses of marine sediments.

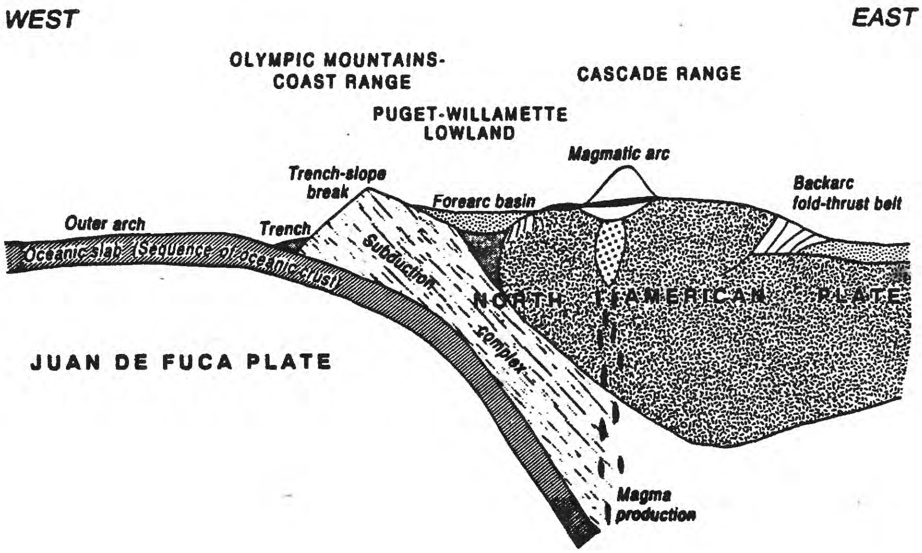


Figure 4.—Diagramatic section showing generalized tectonic features. From Vaccaro (1992).

Pleistocene glaciation further modified the regional geologic setting of the Puget Sound Lowland. There have been at least four glacial and three interglacial periods in the Puget Sound Lowland. The Cordilleran ice sheet, which originated in the Coast Range in British Columbia, advanced into the Puget Sound Lowland at least four times, and several partial glacial advances have been identified in the northern part of the Puget Sound Lowland (Crandell and others, 1958; Armstrong and others, 1965; Blunt and others, 1987). The major advances of the ice sheet intrusions occupied most of the lowland areas and extended laterally into the lower mountain valleys. Alpine glacial advances originating in the Cascade Range and the Olympic Mountains also extended into the Puget Sound Lowland (Booth, 1987). These alpine glacial advances generally were out of phase with the Cordilleran ice sheet.

During the interglacial periods, including the present time, the bordering mountains have provided a large sediment source for the major rivers debouching onto the lowlands. Large alluvial valleys are present along all the major rivers. Alluvial and related sedimentary deposits are known to be more than 600 ft thick in some of the valleys.

As a result of the Holocene-Pleistocene geologic history, the Quaternary deposits consist of nonglacial sediments alternating with one to four regional drift sequences. Additional local sequences occur in parts of British Columbia, Canada and Whatcom County, Wash. (the Fraser-Whatcom Basin), and in parts of the north-central Puget Sound Lowland. The distribution and thickness of these unconsolidated deposits is related to the configuration of the preglacial bedrock surface, the lithology of the bedrock, and the positions of preglacial, glacial, and postglacial stream channels. The interlayered drift and interglacial deposits, as much as 3,300 ft thick, overlie less permeable Tertiary and older rocks in the Puget Sound Lowland. These marine and non-marine sedimentary, volcanic, volcaniclastic, and metamorphic rock units compose the base to the aquifer system and are named the basement confining unit.

During the early stages of the structural development of the Willamette Lowland, lava flows of the Miocene-age Columbia River Basalt Group, originating in the Columbia Plateau of eastern Washington and Oregon, crossed into the Willamette Lowland. Many flows followed the ancestral Columbia River valley and other low areas and flowed to the Pacific Ocean. Some of these flows also extended north into Washington to Chehalis, Wash., and south into the Willamette Lowland to Albany, Oreg. Subsequent late-Tertiary volcanism and uplift resulted in subsidence of the area between the Coast and Cascade Ranges, establishing the Willamette Lowland as a major depositional basin for continental sediments. Volcanism, erosion, further establishment of drainage networks, and Quaternary alpine glaciation provided the sediment sources and processes to deposit basin-fill sediments in much of the Willamette Lowland south of the Portland Basin.

In the northern part of the Willamette Lowland, the Portland Basin, the Columbia River transported and deposited large volumes of sediment from source areas outside the Willamette Lowland. The fine-grained character of much of the lower sections of this basin fill indicates a low-energy environment with a slow depositional rate. Volcanism in the Cascade Range gradually increased and resulted in the deposition of coarser-grained basin-fill sediments. Volcanism also resulted in a number of eruptive centers and lava flows in the northern part of the Willamette Lowland during this stage. These Pliocene-Pleistocene volcanics, the Boring Lava, are compositionally similar to and related to volcanics of the High Cascades. Later Pleistocene geologic and hydrologic processes resulted in erosion and deposition of glacier-derived rock materials. Extensive coarse-grained (generally gravel) alluvial fans are present in the subsurface. The fans are present on the east side of the lowland where major streams that originate in the Cascade Range enter the lowlands. Later, glacial-outburst floodwaters originating from massive ice-dammed lakes in the upper Columbia River Basin inundated the Willamette Lowland, created backwater lakes in the central and southern parts, and deposited sand and gravel north of Oregon City, Oreg., and silt and fine sand throughout most of the remaining areas below about 400 ft in altitude.

As a result of this geologic history, the northern part of the Willamette Lowland aquifer system includes Tertiary lava flows, later Tertiary fluvial sediments, early Quaternary volcanics, and Quaternary alluvium. The aquifer system contained in the structural basin south of Albany, Oreg., the southern Willamette Valley, consists of the basin-fill sediments as thick as 600 ft. The deposits that compose the aquifer system overlie less permeable Tertiary marine sediments and volcanics and non-marine volcanics. As with the units in Puget Sound aquifer system, these rock units form the basal and lateral boundaries of the Willamette Lowland aquifer system and also are named the basement confining unit.

Aquifer Systems

The Puget Sound and the Willamette Lowland aquifer systems share some common features, but in other respects, are quite different. There are several common features:

- The two aquifer systems were formed as a result of glaciation;
- They received meltwater from alpine glaciers;
- They are north-south elongated systems;
- Both are bounded on the east by the rocks of the Cascade Range;
- Both are bounded on the west by the marine rocks of the Olympic Mountains and Coast Range;
- They both include extensive unconsolidated sediments which contain large volumes of potable ground water;
- Their geologic structure separates the aquifer systems into basins;
- The lateral and basal boundaries of the aquifer system is principally composed of pre-Tertiary and Tertiary marine and non-marine sedimentary and volcanic rock units; and
- Rivers drain water from the adjacent mountains through both of the systems.

The two aquifer systems are different in several ways:

- The Puget Sound Lowland has been inundated by at least four continental glaciations, but the continental glaciers did not extend into the Willamette Lowland;
- Alpine glaciers extended into the lowlands of the Puget Sound Lowland; alpine glaciers did not extend into the valley floor of the Willamette Lowland;
- The unconsolidated deposits of the Puget Sound aquifer system are predominantly glacial and interglacial deposits; the unconsolidated deposits of the Willamette Lowland aquifer system are predominantly basin-fill sediments and alluvial deposits;

- The Puget Sound aquifer system is composed only of unconsolidated sediments; the Willamette Lowland aquifer system also includes consolidated rocks—predominantly Miocene basalts of the Columbia River Basalt Group;

- The topography of the low-lying structural basins in the Willamette Lowland is more uniform and flatter than the topography of the Puget Sound Lowland;

- The central drains of the Puget Sound Lowland are Puget Sound and Hood Canal, which are deep saltwater arms of the Pacific Ocean; the central drains of the Willamette Lowland are the Willamette and Columbia Rivers, which are freshwater.

A major difference is that the depositional processes that formed the aquifer systems are very different. This, in conjunction with the physical separation between the systems, the effects of saltwater boundaries, the ground-water discharge locations, and the hydrologic controls of topography, results in two distinct aquifer systems with different types of flow systems. Although the hydraulic characteristics and ground-water recharge processes of the two systems are similar, there are few other hydrogeological similarities between them. Therefore, the two systems were studied independently, but using similar techniques. Additionally, the extent and complexity of the topics of investigation for each system vary.

The study area for the Puget Sound aquifer system includes nearly the complete Puget Sound drainage, mountain crest to mountain crest. Of the 17,616 mi^2 of the Puget Sound Lowland study area, the Puget Sound aquifer system underlies about 7,300 mi^2. Additionally, of the alluvial, glacial, and interglacial deposits of Quaternary age that compose the aquifer system and are present at land surface (excluding large surface-water bodies), about 1,570 mi^2 are recent alluvial deposits, 3,320 mi^2 are fine-grained (clay-to-silty sand) deposits, 2,293 mi^2 are coarse-grained (sand-to-gravel) deposits. These deposits consist of more than 50 named stratigraphic units and represent a complex and highly variable surficial cover to the aquifer system. Because these surficial deposits are important for defining units in the subsurface and because they affect ground-water recharge, the compilation of the Quaternary surficial geology in terms of hydrogeologic units was a primary objective. Defining the total thickness of the deposits was also a major focus of the study. As a result, detailed identification and mapping of the thickness and structure contours of the tops or bottoms of the regional hydrogeologic units was limited.

The study area for the Willamette Lowland part of the RASA was defined by the extent of the units that compose the Willamette Lowland aquifer system and was further limited to the extent of the units in the low-lying parts of the Willamette River drainage. Unlike the study area of the Puget Sound Lowlands, the Willamette Lowland study area did not extend from mountain crest to mountain crest. Of the 5,680 mi^2 study area, the Willamette Lowland aquifer system underlies 3,665 mi^2, of which about 60 mi^2 is overlain by large rivers and lakes. The alluvial, basin-fill, and volcanic deposits that compose the aquifer system underlie about 790 mi^2, 2,295 mi^2, and 2,600 mi^2, respectively. These deposits consist of about 11 named stratigraphic units. Excluding the Portland Basin, these deposits generally represent units that are more readily mapped than the units in the Puget Sound Lowland. Additionally, maps of hydrogeologic units were available for the Portland Basin (Swanson and others, 1993). Therefore, detailed identification and mapping of hydrogeologic units were completed for the Willamette Lowland aquifer system.

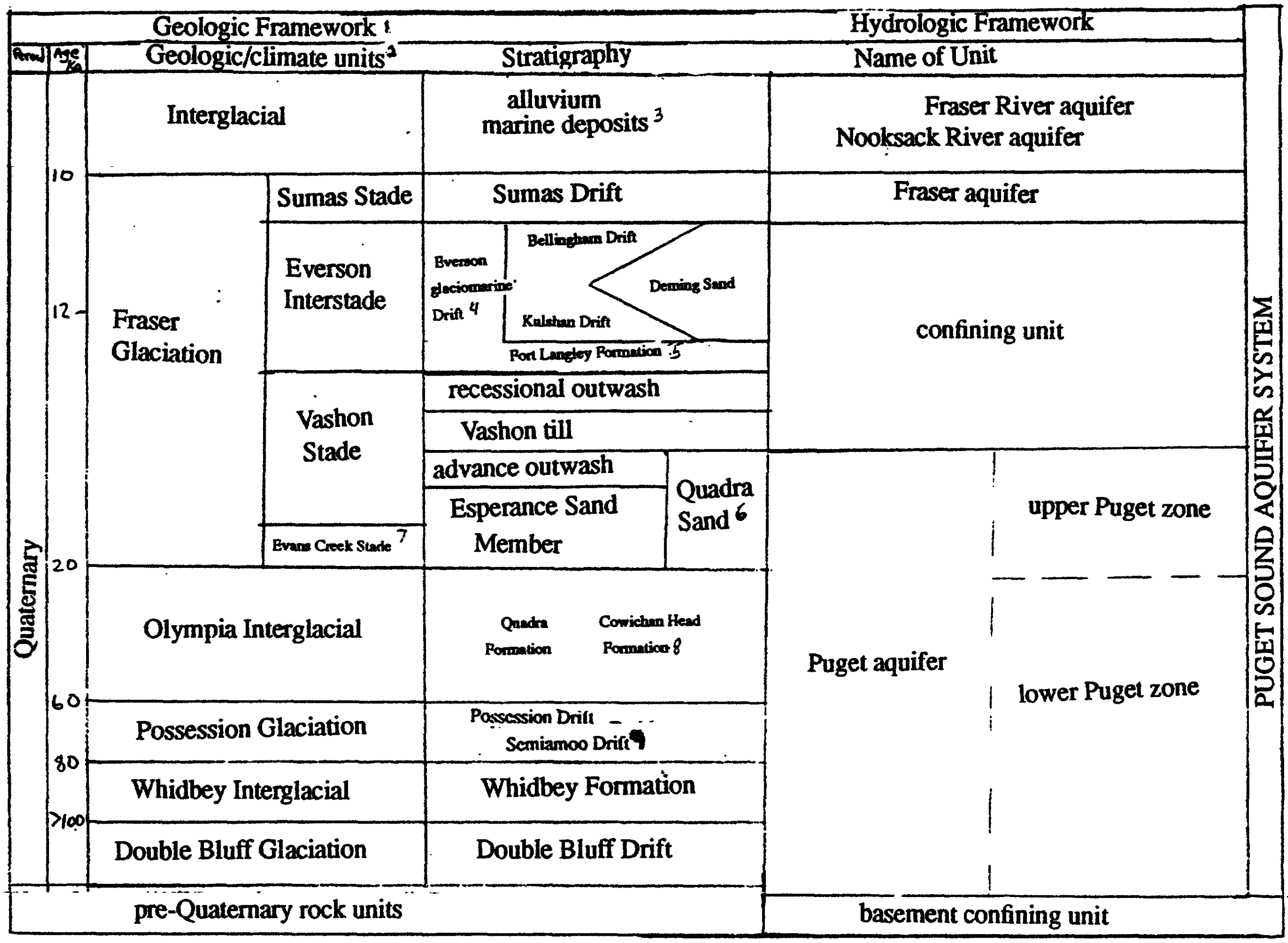
A well inventory was needed for the Willamette Lowland because hydrogeologic units were to be mapped in the subsurface. The well inventory allowed for identification of most major ground-water withdrawals and in addition, a detailed assessment of ground-water use was recently completed for the Portland Basin (Collins and Broad, 1994). Thus, a detailed assessment of water use was completed for the part of the Willamette Lowland south of the Portland Basin. Water-use was estimated for the Puget Sound Lowland on the basis of a recent (1991-92) compilation (R.C. Lane, U.S. Geological Survey, written commun., 1992).

PUGET SOUND AQUIFER SYSTEM

Geology

There have been four recognized glaciations in the Puget Sound Lowland (fig. 5). These major glacial advances occupied most of the lowland and extended laterally into the lower mountain valleys. Alpine glacial advances also extended into the Puget Sound Lowland. Alpine glacial deposits are present at land surface mainly at the higher altitudes in the mountainous areas, predominantly in the southeastern part of the study area. In other areas, the Cordilleran ice sheet has overridden the alpine glacial deposits.

Fraser-Whatcom Basin

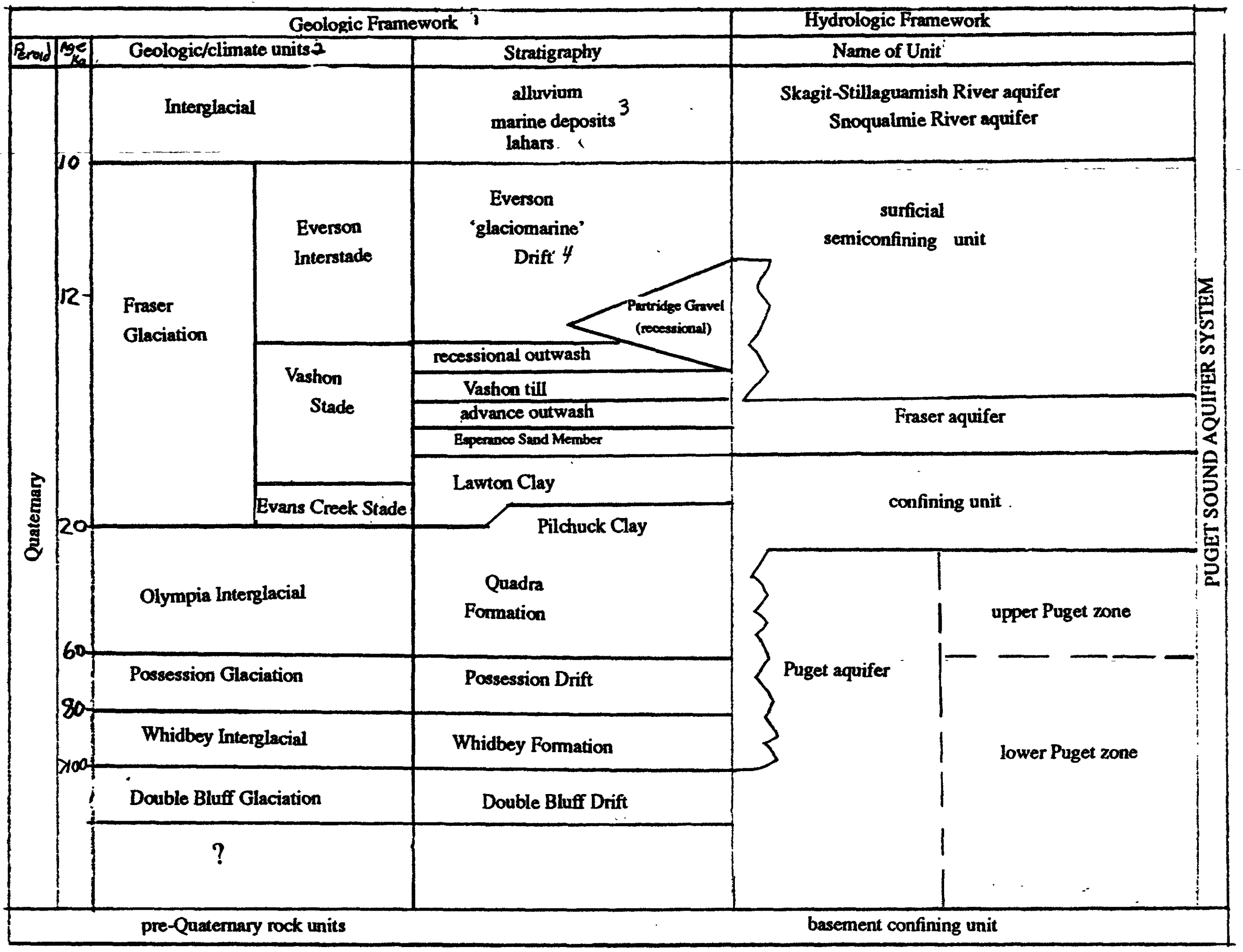


1. Modified from D. Molenaar (written communication, U.S. Geological Survey, 1982) P.C. Haase (written communication, U.S. Geological Survey, 1988), Blunt and others (1987), and Galster and Coombs (1989)
2. Drift sequences are generally separated by unconformities
3. Marine deposits are considered part of aquifer system where saturated with freshwater
4. Also includes glaciofluvial sediments--Everson sand (early Everson) and Everson gravel (late Everson)
5. Canadian name for Everson glaciomarine Drift
6. Canadian name for Vashon deposits older than till, although in many locations the unit does not include the advance outwash
7. Deposits of similar age and older than Evans Creek Stade generally not exposed in the basin, inferred from well-log information and from some exposures in Canada
8. Canadian name for Olympia Interglacial deposits
9. Canadian name for pre-Olympia Interglacial deposits

a) Fraser-Whatcom Basin

Figure 5.--Correlation chart showing the regional relation between stratigraphic and hydrogeologic units for the Puget Sound aquifer system: (a) Fraser-Whatcom Basin, (b) north-central Puget Sound Lowland, and (c) southern Puget Sound Lowland. Location of areas shown on figure 6. From Jones (in press) and Vaccaro and others (in press).

North-central Puget Sound Lowland



1. Modified from D. Molenaar (written communication U.S. Geological Survey, 1982), P.C. Haase (written communication, U.S. Geological Survey, 1988), Blunt and others (1987), and Galster and Coombs (1989)
2. Drift sequences are generally separated by unconformities
3. Marine deposits are considered part of aquifer system where saturated with freshwater
4. Also includes glaciofluvial sediments--Everson (early Everson) and Everson gravel (late Everson)

b) north-central Puget Sound Lowland

Figure 5.--Continued.

Southern Puget Sound Lowland

Geologic Framework[1]				Hydrologic Framework		
	Geologic/climate units[2]		Stratigraphy	Name of Unit		
Quaternary	Interglacial		alluvium, Electron Mudflow[3], Osceola Mudflow[3], lahars, marine deposits[3]	Nisqually River aquifer, Green River aquifer, Puyallup River aquifer, Snoqualmie River aquifer, Skokomish River aquifer, Chehalis River aquifer		
Quaternary	Fraser Glaciation		alluvium			PUGET SOUND AQUIFER SYSTEM
Quaternary	Fraser Glaciation	Vashon Stade	Vashon Drift: Steilcoom gravels; recessional outwash; moraine deposits; Vashon till[4]; advance outwash; Colvos Sand Member	surficial semiconfining unit; Fraser aquifer		PUGET SOUND AQUIFER SYSTEM
Quaternary	Fraser Glaciation	Evans Creek Stade	alluvium; Evans Creek Drift[5]; Skokomish gravels	Fraser aquifer		PUGET SOUND AQUIFER SYSTEM
Quaternary	Olympia Interglacial		Kitsap Formation	confining unit		PUGET SOUND AQUIFER SYSTEM
Quaternary	Salmon Springs Glaciation	upper Stade	"Penultimate Drift"; Hayden Creek Drift[5]; upper Salmon Springs Drift	Puget aquifer	upper Puget zone	PUGET SOUND AQUIFER SYSTEM
Quaternary	Salmon Springs Glaciation	Interstade	sediments, tephra	Puget aquifer	upper Puget zone	PUGET SOUND AQUIFER SYSTEM
Quaternary	Salmon Springs Glaciation	lower stade	Wingate Hill Drift[5]; lower Salmon Springs Drift	Puget aquifer	upper Puget zone	PUGET SOUND AQUIFER SYSTEM
Quaternary	Puyallup Interglacial		Puyallup Formation; Lily Creek Formation	Puget aquifer	lower Puget zone	PUGET SOUND AQUIFER SYSTEM
Quaternary	Stuck Glaciation		Stuck Drift; Logan Hill Formation[5]; Lily Creek Formation	Puget aquifer	lower Puget zone	PUGET SOUND AQUIFER SYSTEM
Quaternary	Alderton Interglacial		Alderton Fromation; Logan Hill Formation[5]; Lily Creek Formation	Puget aquifer	lower Puget zone	PUGET SOUND AQUIFER SYSTEM
Quaternary	Orting Glaciation		Orting Drift; Lily Creek Formation	Puget aquifer	lower Puget zone	PUGET SOUND AQUIFER SYSTEM
pre-Quaternary rock units				basement confining unit		

1. Modified from D. Molenaar (written communication U.S. Geological Survey, 1982), P.C. Haase (written communication, U.S. Geological Survey, 1988), Blunt and others (1987), and Galster and Coombs (1989)
2. Drift sequences are generally separated by unconformities
3. Mudflows and lahars are part of alluvial valley aquifers where confined in channels and not principal unit in channel, otherwise, considered part of surficial semiconfining unit: marine deposits are considered part of aquifer system where saturated with freshwater
4. Vashon till makes up the surficial semiconfining unit where it outcrops at land surface or is covered by only a thin veneer of younger unsaturated deposits
5. Alpine glacial deposits, generally located in mountainous areas of Cascade Range

c) southern Puget Sound Lowland

Figure 5.--Continued.

About 18,000 years BP (before present), the last major advance of the Cordilleran ice sheet reached the northern limit of the Puget Sound Lowland and divided into two lobes. The Juan de Fuca Lobe advanced westward about 120 mi along the Strait of Juan de Fuca to a Pacific Ocean tidewater terminus, and the Puget Lobe advanced southward about 95 mi into the Puget Sound Lowland between the Cascade Range and the Olympic Mountains. As the Puget Lobe advanced, drainage was redirected southward and lakes were formed. Near the southern limit of the Puget Sound Lowland about 14,500 years BP, the Puget Lobe reached its maximum advance, stagnated, and then began to retreat (Thorson, 1980; Blunt and others, 1987). At its maximum extent, the Puget lobe was about 60 mi wide and nearly 4,000 ft thick. The retreat of the Puget Lobe allowed the formation of a series of ice-dammed proglacial lakes, which occupied much of the lowlands. The Juan de Fuca Lobe retreated from the Strait of Juan de Fuca by about 14,500 years BP, allowing for the later draining of the proglacial lakes and the incursion of marine water in the Puget Sound Lowland. The Puget Lobe probably retreated from its terminal position to near the latitude of Seattle, Wash., between 13,500 and 14,500 years BP. The incursion of the marine water allowed the rifting and subsequent melting of the Puget Lobe. In turn, this allowed the deposition of the Everson glaciomarine Drift during the Everson Interstade in the north-central Puget Sound Lowland and the Fraser-Whatcom Basin.

Several partial glacial advances also have been identified in the northern part of the Puget Sound Lowland. For example, during the Sumas Stade of the Fraser Glaciation (fig. 5), the ice sheet readvanced a short distance into the Fraser-Whatcom Basin about 11,500 years BP and totally retreated by about 9,500 years BP (Blunt and others, 1987). As a result, the Sumas Drift overlies part of this basin. Deposits from other partial advances principally occur in the north-central Puget Sound Lowland where they are overlain by either the Vashon or the Everson glaciomarine Drift.

The lateral extent of the Puget Sound aquifer system is generally delineated by the extent of the drift deposited during the Fraser Glaciation—in particular, the Vashon Drift of the Vashon Stade. Except for the Fraser-Whatcom Basin, most of the non-alluvial Quaternary deposits at land surface belong to the Vashon Drift; this drift is relatively undisturbed and close to the land surface.

As a result of the Holocene-Pleistocene geologic history, the Quaternary unconsolidated deposits consist of nonglacial sediments and one to four regional drift sequences and additional local sequences in parts of the north-central Puget Sound Lowland and the Fraser-Whatcom Basin. The drift sequences generally are separated by unconformities and by the nonglacial fluvial and lacustrine sediments. The interlayered drift and interglacial deposits overlie Tertiary and older rocks in the Puget Sound Lowland. Generally, the pre-Tertiary rock units predominate north of the Snoqualmie River; these rock units are older terranes of the North Cascades. The pre-Tertiary and Tertiary rock units compose the base to the aquifer system, the basement confining unit. The total volume of unconsolidated deposits in the study area overlying these rock units is about 1,315 mi^3 (table 1). The similarity between the pattern of the structure contours of the top of the basement confining unit and the thickness contours of the unconsolidated deposits indicates not only that the relief on the top of the basement confining unit is much greater than the land-surface relief, but also that the configuration of the Puget Sound Lowland as a forearc basin was established by about Pliocene time (Jones, in press).

The geologic framework varies across the study area owing to variations in the extent of the major glacial advances, the effects of erosion, the partial glacial advances in the northern part of the Puget Sound Lowland, and the timing of the retreats of the ice lobes. Therefore, the major stratigraphic units (fig. 5) for the Puget Sound Lowland have been presented for the three structural basins (Jones, in press; Vaccaro and others, in press): the southern Puget Sound Lowland, the north-central Puget Sound Lowland, and the Fraser-Whatcom Basin. The Fraser-Whatcom Basin (fig. 6) is unique in that this structural basin is underlain by several thousand feet of continental sediments, and the unconsolidated deposits contained in it generally are separated from the remainder of the aquifer system by about 20 mi of outcrop of the basement confining unit. Additionally, the nomenclature for the stratigraphic units on figure 5 is the most commonly accepted usage for major units. The actual number of named units is more than 50, many of which have been identified during regional, local, or small-scale geologic and hydrogeologic investigations.

In a regional context, three types of deposits are associated with continental glaciers—recessional outwash, advance outwash, and till. The lateral and vertical extent of each of these types of deposits are best known for the Vashon Drift (fig. 5c). Generally, advance and recessional outwash consist of coarse-grained deposits, and the till consists of a fine-grained matrix that contains varying fractions of fine-sand to boulder-size deposits. Although not glacially derived, proglacial deposits are associated with glaciers. Generally, extensive proglacial units, such as the Colvos Sand and the Esperance Sand (fig. 5b,c), have been included with the advance outwash deposits as a hydrogeologic unit in other investigations. Fine-grained, silty-to-clayey deposits generally are associated with interglacial or interstade periods; however, in several small areas, the interglacial deposits are coarse grained. Pre-Vashon age till, outwash, and interglacial type deposits generally are covered by younger deposits and are more difficult to discern; exposures of these deposits are found along coastlines, cliffs, and erosional features. Of the 7,183 mi^2 of unconsolidated Quaternary deposits present at land surface in the Puget Sound Lowland (fig. 6), about 1,570 mi^2 are Holocene alluvial deposits, 3,320 mi^2 are fine-grained deposits, and 2,293 mi^2 are coarse-grained deposits. These deposits have been combined into regional hydrogeologic units.

Table 1.--*Selected information on the physical dimensions of the Puget Sound and the Willamette Lowland aquifer systems*

[mi^3, cubic miles; ft, feet; mi^2, square miles; --, not calculated]

	Puget Sound aquifer system		Willamette Lowland aquifer system
Total volume (mi^3)	1,315		[1]265
Average thickness (ft)	700		[1]450
Areal extent (mi^2)	[2]7,300		[2]3,665
Areal extent of outcrops (mi^2):			
Aquifer units:			
Fraser aquifer	2,755		
Puget aquifer	[3]--	Willamette aquifer	1,640
Alluvial valley aquifers	1,254	Columbia River basalt aquifer	580
Total	4,009	Total	2,200
Semiconfining and confining units:			
Surficial semiconfining unit	2,894	Willamette confining unit	225
Confining unit	397	Willamette silt unit	1,220
Total	3,291	Total	1,445

[1]Does not include volume or the thickness of Columbia River basalt aquifer.

[2]Includes area overlain by large lakes and rivers.

[3]Unit only exposed along cliffs, bluffs, and erosional features; area of exposure is very small.

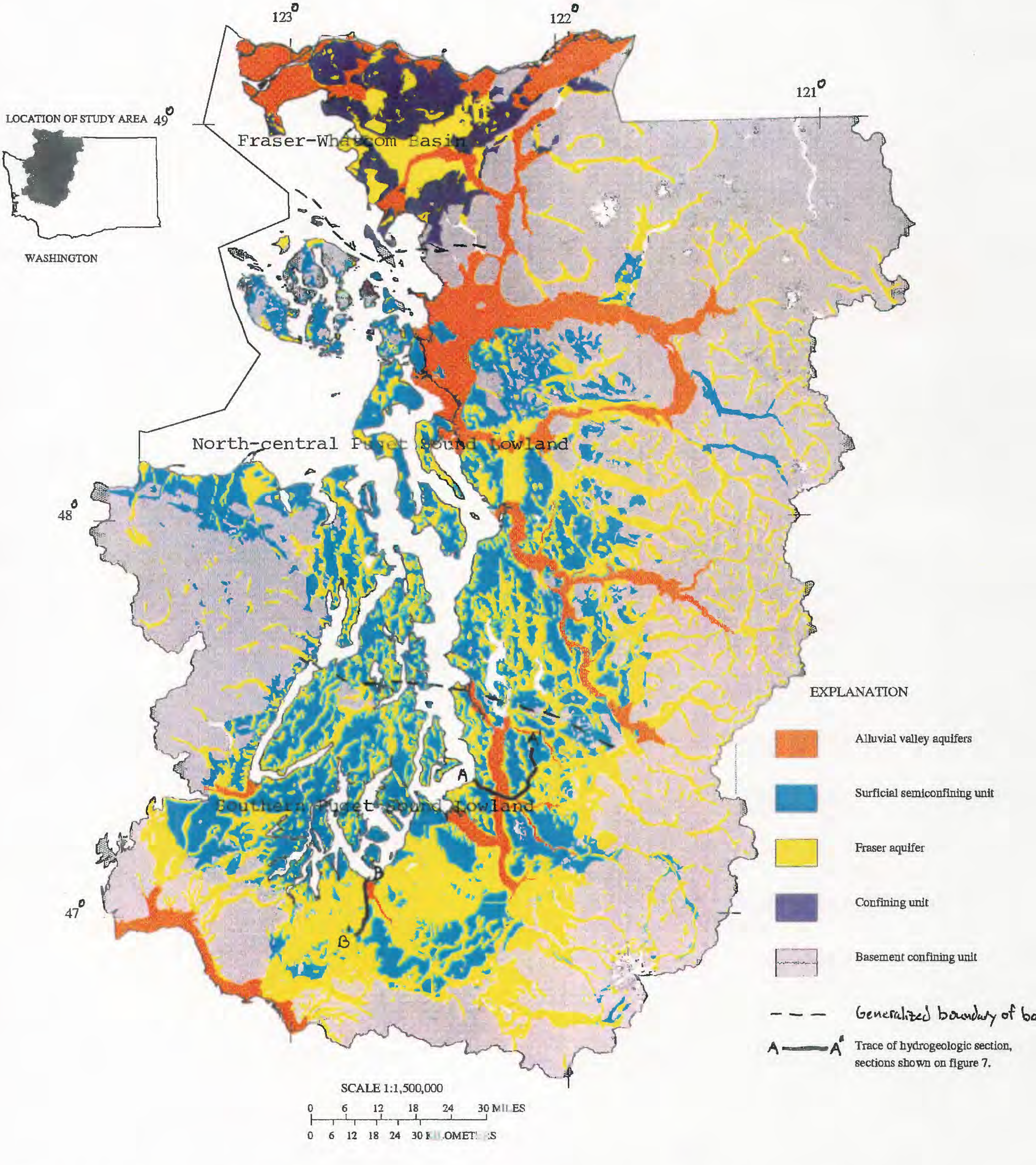


Figure 6.--Generalized extent of regional hydrogeologic units for the Puget Sound aquifer system, and location of major structural basins. From Vaccaro and others (in press) and Jones (in press).

Hydrogeologic Units

The Puget Sound aquifer system is composed of unconsolidated deposits more than 3,300-ft thick (Vaccaro and others, in press; Jones, in press) and consists of materials deposited (1) by at least four advancing and retreating continental glaciations; (2) by numerous alpine glaciers emanating from the adjacent Cascade Range and Olympic Mountains, and by streams during the alpine glaciations; and (3) during interglacial episodes when much of the lowland was covered by saltwater embayments and freshwater lakes, including the present interglacial period. Each of the depositional regimes resulted in complex lithostratigraphic patterns and corresponding geologic units that are difficult to correlate on a regional scale. The complexity within each depositional sequence was compounded by the erosive action of the continental glaciers that altered the pre-existing topography and geology. As a result, the correlation of regional hydrogeologic units with previously named and locally identified stratigraphic and hydrogeologic units is complex.

The unconsolidated deposits compose four types of hydrogeologic units: glacial and interglacial aquifers, alluvial valley aquifers, semiconfining units, and confining units. The coarse-grained aquifer units generally represent outwash deposited during glacial advances and retreats, proglacial deposits, or alluvium deposited during glacial interstades or interglacial periods. The fine-grained semiconfining and confining units generally represent till, lake, glaciomarine, and mudflow deposits. Although recessional outwash channel-fill aquifers are locally important sources of water, they were not defined as separate aquifers for this regional analysis.

Fourteen regional hydrogeologic units have been defined for the Puget Sound aquifer system. From oldest to youngest, these units are the basement confining unit, the Puget aquifer, the confining unit, the Fraser aquifer, the surficial semiconfining unit, and nine alluvial valley aquifers. Figure 5 presents a correlation chart showing the naming conventions for the hydrogeologic units and the relations between stratigraphic and hydrogeologic units. The generalized extent of the surficial regional units is shown on figure 6. The regional units are described below on the basis of the type of deposits and their depositional environment. Additionally, the hydrogeologic units are not necessarily time correlated; that is, the tops and bases of stratigraphic units and hydrogeologic units may differ.

On a regional basis, the part of the aquifer system that consists of the glacial and interglacial deposits (the alluvial deposits present at land surface are described separately) may be considered a sequence of aquifers and semiconfining and confining units. An idealized sequence of the deposits that compose the units for one glacial-interglacial period would consist of, from top to bottom, recessional outwash, till, proglacial deposits, advance outwash, and interglacial deposits. The areal extent of the aquifers in this sequence of deposits generally is limited due to erosional and depositional processes resulting from the advances and retreats of the glaciers and the formation of and deposition in the alluvial valleys. Additionally, topography, the configuration of the basement confining unit, and the presence of saltwater bodies compartmentalize the flow systems in the aquifers.

Recessional deposits present at land surface can be categorized into four groups—(1) locally non-extensive, discontinuous deposits that, depending on the physical setting, may be saturated; (2) laterally and vertically extensive deposits which in some areas directly overlie advance outwash; (3) thick recessional channel-fill deposits which in some areas also overlie advance outwash; and (4) glaciomarine deposits. The first and last groups generally do not function as aquifers, although locally the first group can provide small quantities of water for domestic use. The second and third groups function as aquifers. Each of these groups are considered part of a distinct regional unit, and they are described below with respect to that unit.

The fine-grained (generally till) deposits present at land surface south of the Fraser-Whatcom Basin, limit ground-water recharge and availability. The tills have much larger hydraulic conductivities than the fine-grained (generally lacustrine) interglacial sediments; however, their conductivity generally is one to three orders of magnitude smaller than that of the coarse-grained deposits. Data indicate that the till acts as a semiconfining unit or a low-yield aquifer. Although these deposits do not appear to largely affect the regional flow system (Vaccaro and others, in press), they locally affect ground-water availability, contaminant transport, and surface-water runoff. Therefore, these deposits were defined as a distinct regional unit—the surficial semiconfining unit. Excluding the Fraser-Whatcom Basin, the Everson glaciomarine Drift (fig. 5) is considered to be part of this regional semiconfining unit. Extensive mudflow deposits and local non-extensive recessional outwash deposits also are considered part of this unit. The surficial semiconfining unit overlies about 2,894 mi^2; the thickness of this unit ranges from a few feet to more than 125 ft, and averages between 20 and 40 ft.

On a regional basis, only the shallowest or near-to-sea level fine-grained, clayey deposits that are areally extensive appear to affect the ground-water flow system on a regional scale (Vaccaro and others, in press). These fine-grained deposits are considered a regional confining unit, called the confining unit. Within the Fraser-Whatcom Basin, the confining unit consists predominantly of the Everson glaciomarine Drift which crops out over part of the basin. Where the till directly overlies or underlies the fine-grained deposits, it is considered to be part of this unit. This confining unit is exposed at land surface over 397 mi^2; its total lateral extent is not known and was not mapped during this study, but on the basis of results of previous studies and this study, the area it overlies is about 4,000 mi^2. The thickness of the confining unit locally exceeds 150 ft and averages between 20 and 65 ft.

The aquifer units in the glacial and interglacial sequence consist of all deposits (excluding the surficial semiconfining unit) that overlie or underlie the fine-grained deposits of the confining unit. The aquifer units consist of glacial outwash, proglacial, and locally interglacial, alluvial, and mudflow deposits. Where present, the aquifer unit that overlies the confining unit is called the Fraser aquifer. The Fraser aquifer is essentially the water-table aquifer over much of the area. The Fraser aquifer crops out over 2,755 mi^2 and its lateral extent is 5,500 mi^2. The thickness of this unit averages 40 to 50 ft and locally is as much as 150 ft thick.

Underlying the confining unit is the Puget aquifer, which may be further divided locally into the upper Puget zone and the lower Puget zone. The Puget aquifer is exposed only along cliffs, bluffs, and erosional features. The lateral extent of the Puget aquifer is not known; however, it occurs throughout about 70 to 80 percent of the areal extent of the aquifer system. The thickness of the Puget aquifer generally is more than 400 ft and exceeds 1,000 ft in the major structural basins.

The alluvial valley aquifers are composed of extensive alluvial deposits found in the major river valleys, and they are named after the associated river. These valleys traverse the glacial deposits in the study area, and the rivers in the valleys discharge to saltwater bodies. The alluvial valley aquifers truncate and control the flow systems in the glacial and interglacial deposits, and they typically are linear features. Each of these aquifers closely follows the associated river valley and, on a regional basis, is considered a separate aquifer unit.

In the upper reaches of the rivers in the bedrock-controlled valleys, glacial, interglacial, and mudflow deposits are considered to be part of the alluvial valley aquifer units. This is due to the small extent of these deposits compared with the alluvium and, in many instances, to the similarity of hydraulic characteristics of the alluvium and the continental and alpine glacial deposits. In areas where the mudflow deposits are extensive, they are not included in the alluvial aquifers but are included in the surficial semiconfining unit. Less extensive and also discontinuous alluvial deposits that are not channelized and display similar characteristics to local glacial deposits are not separated as alluvial valley aquifers but are considered part of the surficial semiconfining unit or the Fraser aquifer, depending on the unit they overlie. On the basis of the extent of the alluvium in the major river valleys, nine alluvial valley aquifers were identified and named (fig. 5). These aquifers extend over about 1,254 mi^2 (fig. 6, table 1). The thickness of these aquifers is highly variable and ranges from 10 to 20 ft in the upper valleys to more than 600 ft in some of the lower valleys.

Well-defined, deep, recessional outwash channels that are filled with coarse-grained glacial deposits are productive aquifers. However, many generally are stream valleys and are located in both the bedrock-controlled upper reaches of rivers and in most of the valleys in the southern part of the study area. They were not defined as separate aquifer units but are considered either part of the alluvial valley aquifers or an extension of the Fraser aquifer. Additionally, laterally extensive recessional outwash deposits also are considered part of the Fraser aquifer. These outwash deposits are most prevalent in Pierce and Thurston Counties (near the southern terminus of the continental glaciers) where they generally overlie either advanced outwash, proglacial deposits, or the confining unit.

The simplified regional hydrogeologic units consist of (1) the nine alluvial valley aquifers that may or may not contain other types of deposits, (2) a surficial semiconfining unit, (3) a sequence of coarse-grained aquifers and a fine-grained confining unit (the Fraser aquifer, the confining unit, and the Puget aquifer), and (4) the basement confining unit, which forms the basal and lateral boundaries of the aquifer system. The deposits that compose the aquifer units vary from silty sands to gravels and may locally contain extensive deposits or zones that are more or less productive than the surrounding deposits. The identification of the regional units provides for a simplified conceptual model of the Puget Sound aquifer system for describing regional ground-water flow. Examples of hydrogeologic sections showing the distribution of units in the Puget

Sound aquifer system are shown on figure 7, and table 1 presents information on the physical dimension of the aquifer system and the units that compose the system.

Hydraulic Conductivity

The ranges in values of hydraulic conductivity for the regional hydrogeologic units are presented in table 2. The numerous depositional environments and large variety of source material, and lithologic characteristics have resulted in a wide range of hydraulic conductivity values. Additionally, because the magnitude of the hydraulic conductivity values generally correlates with grain size, the conductivity values indicate the large lithologic variability both within and between regional units in the Puget Sound aquifer system. The ranges in conductivities provide information for describing ground-water flow and, where analyzed in conjunction with the extent of a unit and recharge, for describing ground-water availability.

Although each of the regional hydrogeologic units contains a diverse assemblage of sediments with a wide range of lithologic characteristics, the information presented in table 2 and in Vaccaro and others (in press) indicates two regional aspects. First, both the surficial semiconfining and confining units generally have much smaller conductivities than the aquifer units, and the confining unit has smaller conductivities than the surficial semiconfining unit. The large contrast in hydraulic conductivity between these two units and the aquifer units indicates (1) the two units exert hydrologic control to aquifer units and limit water movement into and between aquifer units and (2) water movement is predominantly vertical in both the surficial semiconfining and confining unit. Second, effective regional values of hydraulic conductivity for the aquifer units generally fall into three categories: (1) the Fraser and Puget aquifers have effective regional values of about 50 ft/d, (2) values between 50 to 100 ft/d indicate areas where the aquifer units contain more coarse-grained materials, and (3) the alluvial valley aquifers and the Fraser aquifer in both the southern part of the study area, where it consists of coarse-grained recessional outwash, and in the Fraser-Whatcom Basin generally have effective values of about 100 to 200 ft/d. For category 3 above, the large hydraulic conductivities and flat topography result in very small hydraulic gradients.

Ground-Water Recharge

Mean annual ground-water recharge to the Puget Sound aquifer system was estimated during the RASA study (Vaccaro and others, in press). The estimates were made on the basis of relations between recharge and mean annual precipitation, surficial geology—areas covered by fine-grained-coarse-grained deposits, and land use and cover. The relations were derived from both daily water-budget models and rainfall-runoff models; the models were applied to 26 basins or areas in previous investigations (Vaccaro and others, in press). Mean annual recharge was estimated on the basis of two relations, one for fine-grained covered areas and one for coarse-grained covered areas. The fine-grained areas generally correspond to the surficial extent of the surficial semiconfining unit and the confining unit, and coarse-grained areas generally correspond to the surficial extent of the Fraser aquifer and the alluvial valley aquifers. The estimated recharge was then reduced on the basis of land use and cover. Estimates were not made for areas overlain by large surface-water bodies or for the basement confining unit.

Mean annual recharge for the area overlying the Puget Sound aquifer system was estimated to be at 27.4 in/yr or 14,510 ft^3/s (about 10,500,000 acre-ft of water—51 percent of the total precipitation; table 3). This estimate includes about a 2-in. or 1,052-ft^3/s reduction due to land use and land-cover effects. For areas covered with fine-grained deposits, recharge was estimated at 17.6 in/yr (36 percent of the precipitation falling on fine-grained deposits) and for coarse-grained covered areas, recharge was about 35.9 in/yr (63 percent of the precipitation falling on coarse-grained deposits). Mean annual unit recharge to the aquifer system is about 2.0 $ft^3/s/mi^2$; however, excluding recharge in the upland and mountainous areas, unit recharge is about 1 $ft^3/s/mi^2$ for the low-lying areas. The rather small value for the lowlands is due to the fact that on a long-term basis, a large area receives less than 10 in/yr of recharge. The estimate of mean annual recharge to the Puget Sound aquifer system is about 60 percent of the median September streamflow and about 26 percent of the median annual streamflow for the Puget Sound drainage. The estimated spatial distribution of mean annual recharge is shown on figure 8, and the results of the analysis are presented in table 3.

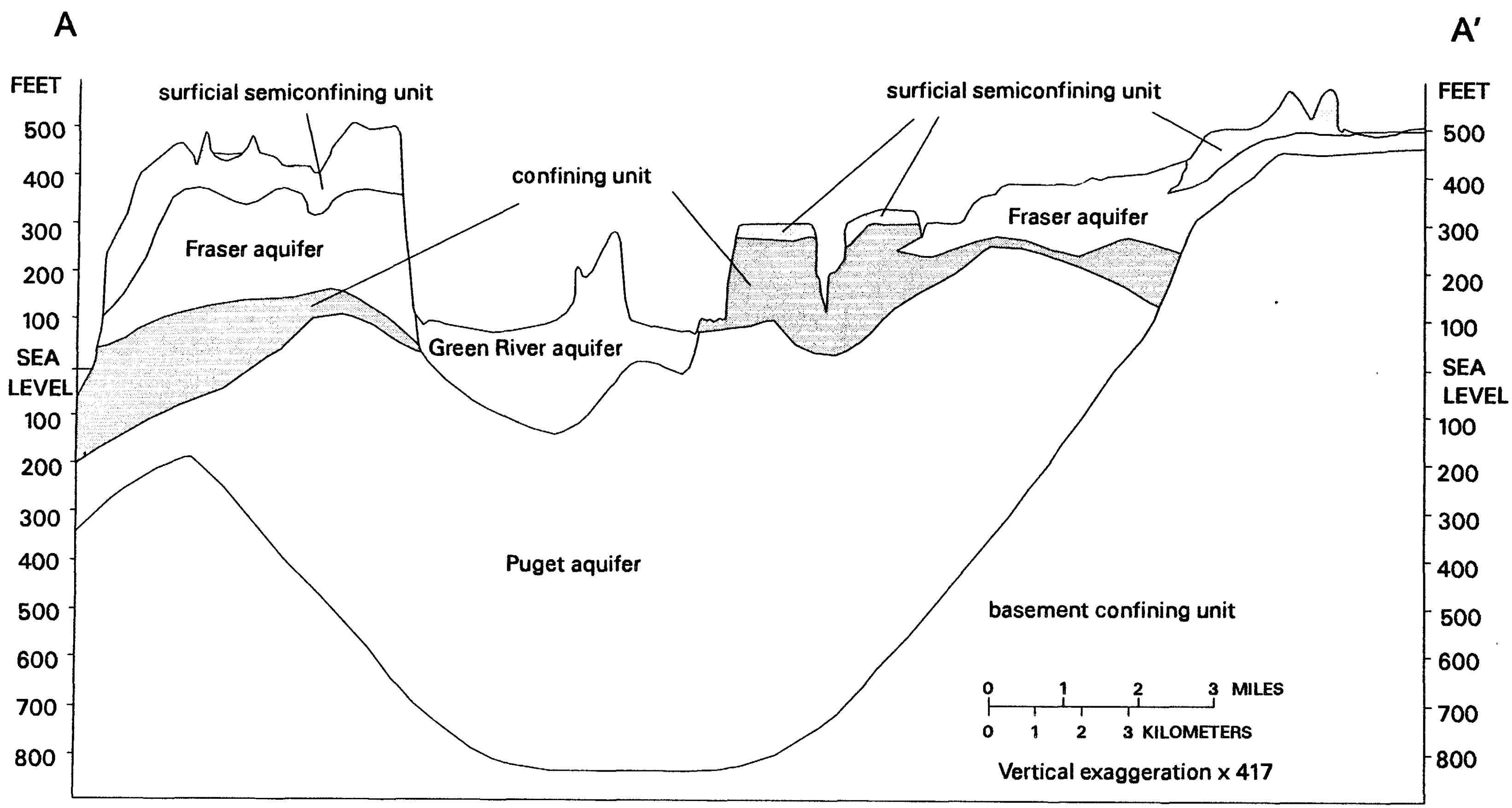


Figure 7.--Hydrogeologic sections for the Puget Sound aquifer system. (From Vaccaro and others, in press). Trace of sections shown on figure 6.

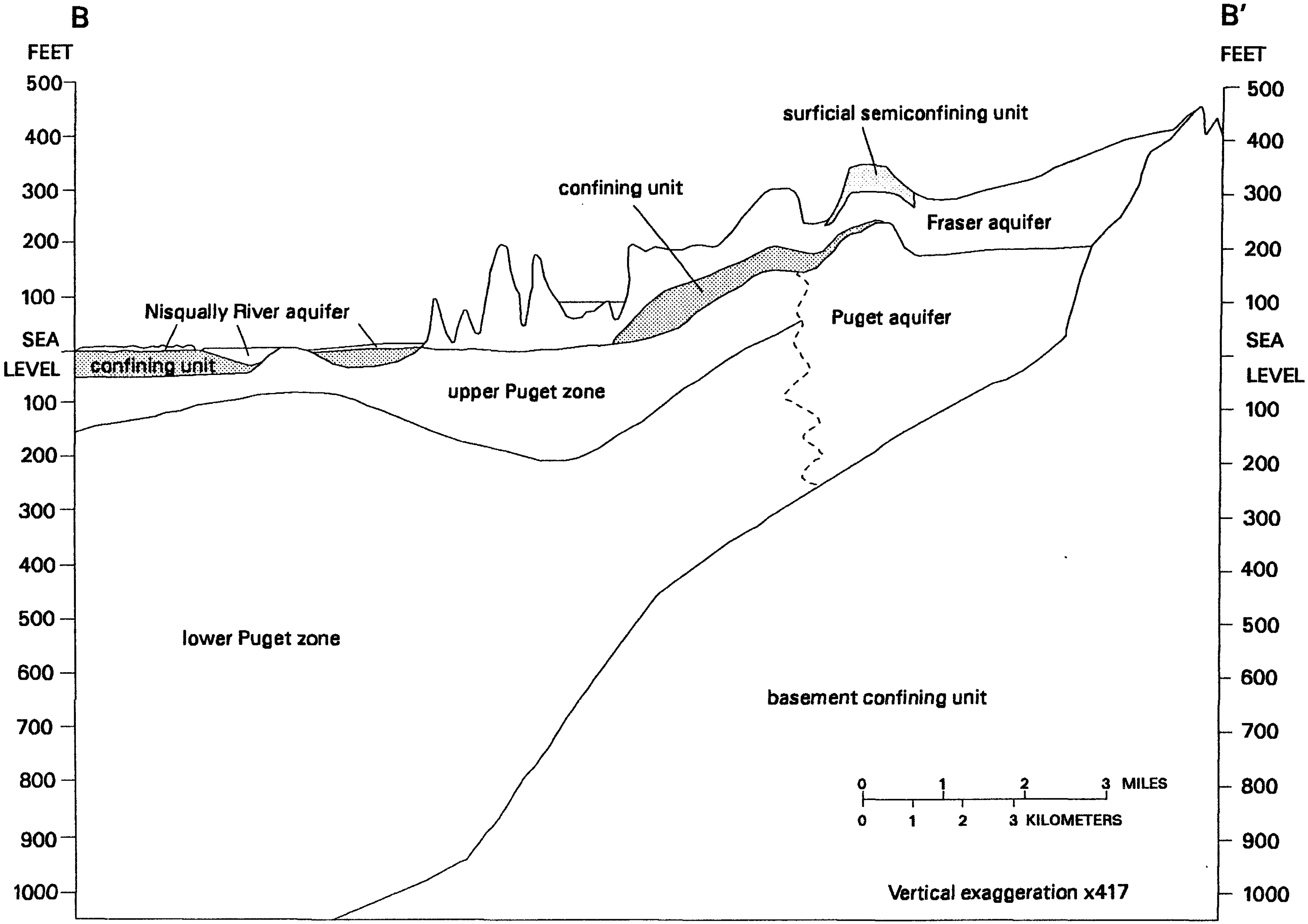


Figure 7.--Continued.

Table 2.--*Estimates of hydraulic conductivity for the hydrogeologic units of the Puget Sound and the Willamette Lowland aquifer systems*

[--, unknown]

Hydrogeologic unit	Number of values[1]	Range (feet per day)	Range in reported average or median values (feet per day)
	Puget Sound aquifer system		
Surficial semiconfining unit	59	0.0003 - 53	0.001 - 1
Fraser aquifer	718	0.02 - 7,000	5 - 800
Confining unit	3	0.00007 - 0.003	0.0001 - 0.002
Puget aquifer	426	0.54 - 5,260	14 - 134
Alluvial valley aquifers:			
Fine-grained	159	1 - 15	7.5 - 8.5
Medium to coarse-grained	397	20 - 7,570	36 - 700
	Willamette Lowland aquifer system		
Willamette silt unit	5	0.01 - 8	0.01 - 8
Willamette aquifer	358	0.03 - 7,000	10 - 240
Willamette confining unit[2]	113	0.01 - 90	1 - 4
Columbia River basalt aquifer[3]	--	0.001 - 750	.1 - 10

[1]Number of values not always reported

[2]Values based on coarse-grained deposits contained in unit

[3]Number of values not reported, and values also based on those presented in Hansen and others (1994)

Table 3.--*Estimates of mean annual recharge for the Puget Sound and Willamette Lowland aquifer systems*

[mi^2, square miles; in/yr, inches per year; ft^3/s, cubic feet per second]

Area (mi^2)	Recharge (in/yr)	Precipitation (in/yr)	Recharge (ft^3/s)	Precipitation (ft^3/s)
		Puget Sound aquifer system		
7,183[1]	27.4	53.2	14,510	28,170
		Willamette Lowland aquifer system		
3,844[1,2]	19.3	46.6	5,463	13,187

[1]Does not include area overlain by large lakes and rivers.

[2]Includes estimates for 179 mi^2 of non-bedrock areas which, for this regional analysis, have been included as part of the basement confining unit.

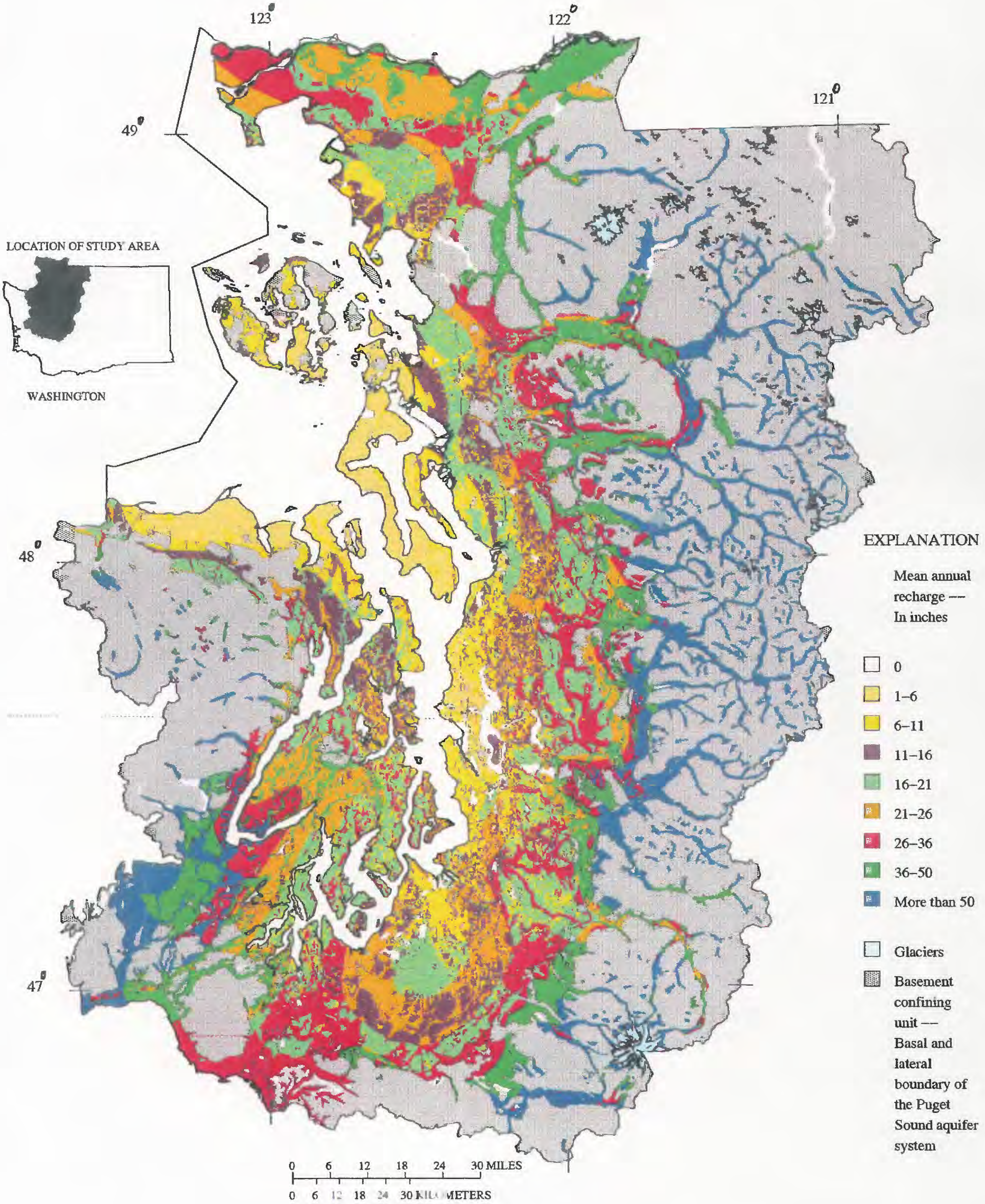


Figure 8.--Estimated distribution of mean annual ground-water recharge for the Puget Sound aquifer system. Modified from Vaccaro and others (in press).

Estimated values of recharge were compared with 7-day low-flow and mean annual discharge values in seven small basins ranging in size from 5.01 to 39.3 mi^2, to ground-water level changes, and to estimates from other studies. This comparison showed that the estimates of recharge were reasonable (Vaccaro and others, in press).

Estimates of annual recharge also were made for sites with small- and large-precipitation quantities (mean annual precipitation of 19 and 53 in/yr, respectively) located in the low-lying parts of the study area, including both types of surficial geology. At the small-precipitation site, recharge estimates range from 0.15 to 12.48 in/yr for fine-grained deposits and from 0.0 to 19.56 in/yr for coarse-grained deposits. The lower value for coarse-grained deposits is due to application of the relations to small values of annual precipitation (less than about 14 in/yr). At the large precipitation site, recharge ranged from 10.7 to 35.5 in/yr for fine-grained deposits and from 16.7 to 56.9 in/yr for coarse-grained deposits. The results indicated the large potential temporal and spatial variability in recharge and further showed that the mean annual estimates derived during this study are averages of widely varying values.

Ground-Water Flow System

Regionally, ground-water movement generally is from topographic highs to lows. The direction of movement is predominantly lateral in the aquifer units and vertical in the semiconfining and confining units; however, water moves both horizontally and vertically in all units. Vertical gradients generally are downward, except near larger streams and saltwater bodies where gradients are upward; generally water moves downward to deeper units in high-altitude areas and upward from deeper units to shallower units in the low-altitude areas. Ground water in the uppermost aquifer unit generally is under unconfined conditions and water in the deeper units generally is under confined conditions.

Movement of ground water is controlled by topography, geometry of the aquifer system, depth of saltwater bodies and configuration of the shoreline, configuration of the basement confining unit, distribution and rate of ground-water recharge, and hydraulic conductivity of the aquifer system. The pattern of ground-water movement (fig. 9) indicates the regional aspects of the controls.

Topographic control is shown by the short flow paths from topographic highs to lows. Many of the flow paths terminate at the alluvial valley aquifers or at salt water. The former shows the control of the regional geometry of the aquifer system, particularly the alluvial valley aquifers. The latter shows the control of saltwater boundaries—flow paths terminate at salt water. The geometry of the basement confining unit provides control through the thickness of the aquifer system—where the top of this unit is deep, the deposits are thick and can store and transmit more water, and where the top is near or at land surface, the unit truncates and partitions the flow system. The hydrologic control of topography, geometry of the aquifer system, saltwater bodies, and the basement confining unit results in isolated, generally local flow systems; under present (1994) pumping conditions, there is no regional flow system. The control provided by recharge is not directly shown by the pattern of ground-water movement; recharge provides control by establishing a limit on the total quantity of ground water that moves within the local flow systems. The hydraulic conductivity affects the rate of water that moves within the system, and it also affects the lateral and vertical hydraulic gradients in local-to-subregional flow systems.

Selected controls on ground-water movement in these flow systems are described below on the basis of analyses of regional water-level configurations and results of seven cross-sectional numerical models of ground-water flow presented in Vaccaro and others (in press).

The effective length and altitude difference between a topographic high and a principal discharge location (salt water or an alluvial valley aquifer) define the topographic control on the flow system. This control includes the presence of bluffs. A topographic high must extend over a distance of about 2,000 to 5,000 ft and have vertical relief of about 100 ft or more in order to provide control to the flow system. Topography provides minimal control on the flow system in the low-relief alluvial river valleys.

Except where flow systems terminate at the alluvial valley aquifers, at bluffs in the upper sections of the glacial deposits, or at bedrock, flow systems terminate at a freshwater-saltwater boundary. Along the shoreline, salt water provides control to the Puget aquifer throughout most of the area and to the Fraser aquifer where the top of the confining unit is below sea level. In the presence of saltwater boundaries and a deep top of the basement confining unit, salt water provides the most important hydrologic control. Generally, there is a transition of control from the basement confining unit to salt water as ground water moves from the beginning of a flow path to its terminus.

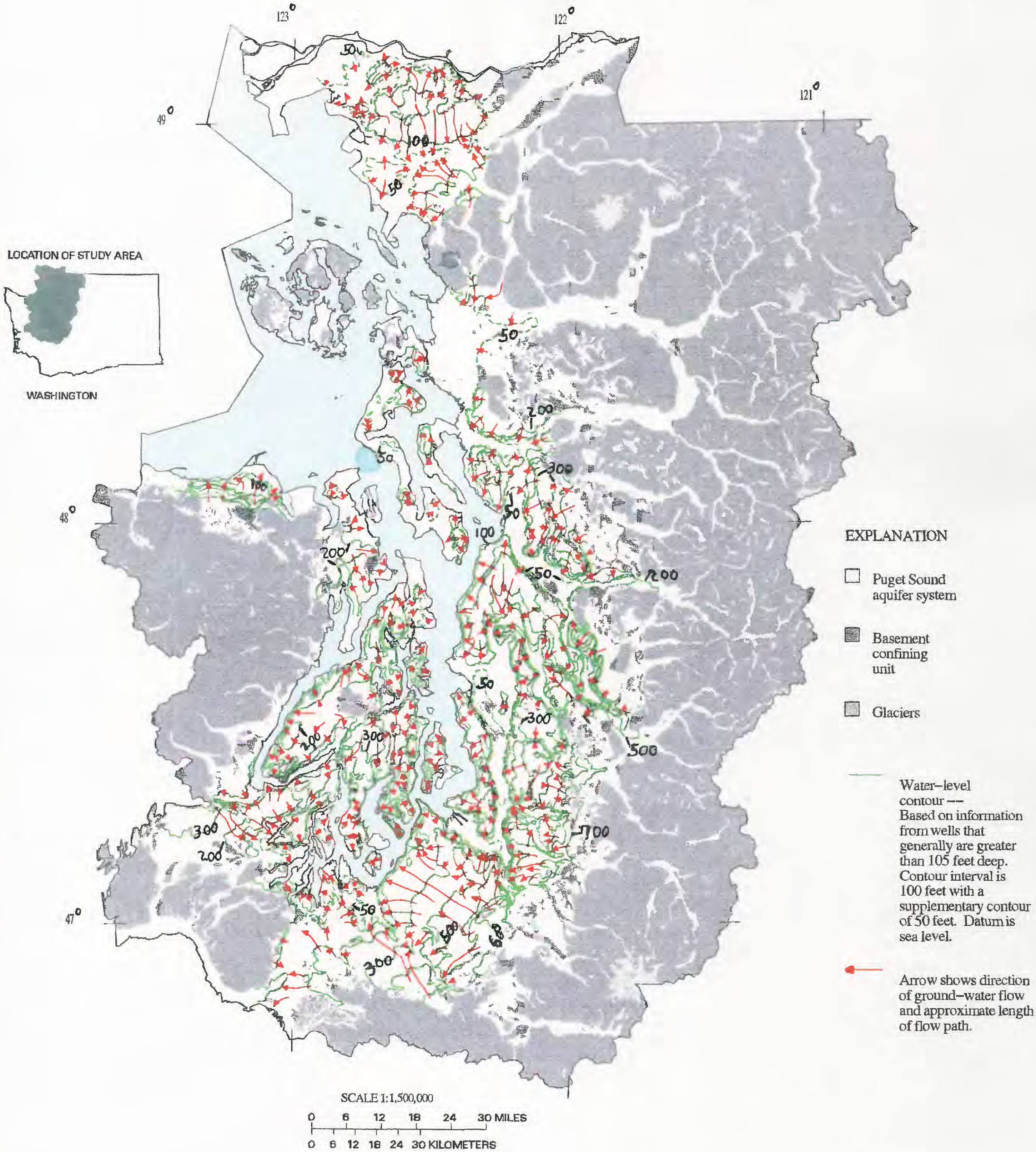


Figure 9.--Generalized pattern of ground-water movement for the Puget Sound aquifer system. Lateral hydraulic gradients are indicated by spacing of generalized water-level contours. Detailed water-level contours presented in Vaccaro and others (in press).

Ground-water flow-path lengths range from about 1,000 ft in the upper parts of the aquifer system to about 15 mi in the deeper parts of the system. Except for very localized flow systems with flow paths about several hundreds of feet long, most flow paths generally range from 2 to 7 mi; maximum lengths of flow paths within the Puget Sound aquifer system are about 20 mi in southeast Pierce County. Flow paths within the alluvial valley aquifers generally are 0.5 to 4 mi long. The lengths of flow paths and the pattern of ground-water flow indicate that a connected, subregional flow system exists only in the Fraser-Whatcom Basin and in part of the southern Puget Sound Lowland.

Excluding the alluvial valley aquifers, horizontal gradients generally range from 10 to 70 ft/mi (0.002 to 0.010 ft/ft); on a regional basis, the average is about 30 ft/mi (0.006 ft/ft). The smaller gradients are in coarse, recessional outwash deposits or where the topography is relatively flat. The largest horizontal gradients (0.010 ft/ft) are in the Fraser aquifer in steep terrain near bluffs; these gradients generally correspond to the altitude difference between the top of a bluff and the base level of the discharge area (either at sea level or the top of an alluvial valley aquifer. The locations of bluffs are clearly identified where the water-level contours are close (fig. 9). Generally, horizontal gradients in the Puget aquifer are smaller than those in the Fraser aquifer and average about 20 ft/mi (0.004 ft/ft). Within the alluvial valley aquifers, horizontal gradients are about 5 ft/mi (0.0009 ft/ft); the small gradients indicate the effects of relatively flat topography and large hydraulic conductivity. Although the glacial deposits locally are as permeable as the alluvium, topographic control and the heterogenous nature of the glacial deposits result in larger gradients. Horizontal gradients in the surficial semiconfining unit and, where known in the confining unit, average about 100 ft/mi (0.02 ft/ft).

Vertical gradients range from about 0.005 to 1.6 ft/ft and regionally average about 0.3 ft/ft. Vertical-head differences generally range from 1 to 200 ft. The smallest gradients generally are in the alluvial valley aquifers and the largest are in areas of large topographic relief near bluffs. Locally, the largest vertical gradients are across the confining unit. Within the Fraser aquifer, most vertical gradients are downward, and within the thicker sections of the alluvial valley aquifers, most gradients are upward. Vertical gradients in the Puget aquifer generally show a transition from downward to upward. This transition zone may occur several thousands of feet downgradient from a bluff, near the boundary of an alluvial valley aquifer, or near the shoreline. For the latter case, the topographic setting near the shoreline affects the location of the transition zone. Where the topography is relatively flat or relief is small, the zone will be some distance inland; this distance also is controlled by other factors such as aquifer-system geometry, hydraulic characteristics, and recharge. Where bluffs abut the shoreline, the transition is close to the shoreline.

Unit recharge along flow paths in the non-mountainous areas ranges from about 0.20 to 1.5 $ft^3/s/mi^2$; in the mountainous areas, unit recharge is more than 5 $ft^3/s/mi^2$. The first two values are between the 25th and 80th percentile values of the 7-day unit low flows for the Puget Sound region. Unit discharge to seeps, springs, and small streams generally ranges from 0.25 to 1.25 $ft^3/s/mi^2$, and unit discharge to saltwater bodies generally ranges from 0.10 to 0.25 $ft^3/s/mi^2$. The unit discharge to salt water indicates that total discharge is between 100 and 1,000 ft^3/s (Vaccaro and others, in press). Unit discharge to major rivers in the alluvial valley aquifers ranges from 0.30 to 0.90 $ft^3/s/mi^2$ in the non-mountainous areas and is more than 5 $ft^3/s/mi^2$ in the mountainous areas. Although the latter value is large, it should be noted that the extent of the alluvial valley aquifers in the mountainous areas is small compared with the rest of the aquifer system.

Water Use

The largest water uses in the Puget Sound Lowland are agricultural, municipal, and industrial; livestock water use is small. In 1965 for the part of the study area located in the United States, agricultural water use was about 202 Mgal/d, municipal use was 219 Mgal/d, and industrial use was about 431 Mgal/d, about 75 percent of which was associated with the manufacturing of paper. Domestic water use was only 9 Mgal/d of the total water use in 1965, which was 861 Mgal/d. About 85 percent of the 1965 withdrawals (732 Mgal/d) was derived from surface-water sources and the remainder (129 Mgal/d) was derived from ground-water sources. On the basis of county-wide information for 1975 (Dion and Lum, 1977), municipal water use appeared to be increasing and industrial water use seemed to be decreasing for the period 1965-75. For example, the estimated 1975 municipal use was 461 Mgal/d and industrial use was 316 Mgal/d.

R.C. Lane (U.S. Geological Survey, written commun., 1992) has estimated water use for the Puget Sound region for 1990 for the part of the study area within the United States as part of a nationwide assessment of water use. Lane estimated quantities for 1990 by water-use category (see table 4 for ground-water quantities) and calculated a total of 810 Mgal/d. About 497 Mgal/d of the total was for public supplies, of which about 35 percent (174 Mgal/d; 269 ft^3/s) was provided by ground-water sources, and about 65 percent (323 Mgal/d; 500 ft^3/s) was provided by surface-water sources. The remaining 313 Mgal/d was privately supplied (57 percent (178 Mgal/d; 275 ft^3/s) from ground-water sources and 43 percent (135 Mgal/d; 209 ft^3/s) from surface-water sources). Whereas Dion and Lum (1977) considered industrial use to include most commercial use and considered municipal use to include principally domestic use, Lane has separated out these quantities. However, as of 1990, industrial and commercial water use still appears to be declining, as does irrigation water use. Although municipal domestic water use appears to have decreased from 1975, other uses were included in the municipal category for 1975.

From 1965 to 1990 there has been an estimated reduction in total water use. This may be due to the reduction of large industrial uses (such as the manufacturing of paper) resulting from the conversion and diversification of the economic base of the region. However, in 1990 the estimated 352 Mgal/d (444,710 acre-ft; 544 ft^3/s; table 4) of water supplied from ground-water sources is nearly two times (or 223 Mgal/d) more than the quantity supplied from ground-water sources in 1965. Additionally, for 1988, the estimate of water supplied from ground-water sources for the part of the Puget Sound aquifer system in Canada was about 182 Mgal/d (203,880 acre-ft; 282 ft^3/s; table 4).

As population and industrial growth continues, more water is being derived from ground-water sources rather than from surface water. In some areas, surface water is nearly fully appropriated, and unappropriated surface water is far from the locations of need. Thus, most new and smaller water-supply systems are using ground water as their source. The estimate of total ground-water use, 534 Mgal/d or about 826 ft^3/s, is only about 6 percent of the estimated mean annual recharge. However, like surface-water supplies, much of this recharge occurs in the mountainous regions, far from the locations of need, and the remainder occurs as diffuse recharge to the Fraser aquifer and the alluvial valley aquifers. For the latter case, the heterogenous nature of the Fraser aquifer, combined with the predominance of local flow systems and short flow paths (small contributing area of recharge, and hydraulic connection of the aquifer with surface water), precludes extensive development of local well fields.

Table 4.--*Estimates of ground-water use for the Puget Sound and Willamette Lowland aquifer systems*

[Values are rounded; Mgal/d, million gallons per day; ft^3/s, cubic feet per second; acre-ft/yr, acre-feet per year; --, included in public-supply category; NA, not applicable]

	Puget Sound aquifer system			Willamette Lowland aquifer system		
Use	Mgal/d	ft^3/s	acre-ft/yr	Mgal/d	ft^3/s	acre-ft/yr
			United States (1990)			
Public supply	174	269	194,910	62	96	69,600
Industrial-Commercial	36	56	40,330	64	100	72,150
Irrigation-Livestock	83	128	143,380	174	269	194,500
Domestic	59	91	66,090	--	--	--
			Canada (1988)			
All categories	182	282	203,880	NA	NA	NA
Total	534	826	648,590	300	465	336,250

Ground-Water Quality

Historical ground-water quality data for selected constituents for the part of the study area within the United States are summarized in table 5; both the average and median values of the analyses are presented. The data are based on 5,131 analyses that were in the U.S. Geological Survey's national data base as of October 1992. Ground-water quality investigations of the part of the aquifer system in Canada have been completed by Kwong (1986), Liebscher and others (1992), and Kohut and others (1989), and selected results from these investigations are briefly described in this section.

Calcium bicarbonate, magnesium bicarbonate, and calcium-magnesium bicarbonate are the dominant water types in the shallow parts of the aquifer system. Deeper parts of the aquifer system contain water of a sodium bicarbonate or a sodium chloride type. Generally, sodium bicarbonate water types have been attributed to proximity with consolidated bedrock, to long residence time in the ground-water system, and to the presence of fine-grained marine deposits of recent age (Whiteman and others, 1983; Dion and others, 1988; Dion and others, 1994). The sodium bicarbonate water types also contain larger concentrations of dissolved solids than other water types. Sodium chloride water generally is associated with mixing of native ground water with seawater; these water types also have larger concentrations of magnesium than most other water types.

Ground water generally is soft to moderately hard as indicated by the median hardness value of 60 mg/L (table 5). The hardness is determined by the calcium and magnesium concentrations of the ground water; in areas with larger concentrations of these constituents, the water may vary from hard to very hard (for example, in parts of San Juan and Island Counties) (Turney, 1986). Because sodium is not a dominant cation in the ground water in the aquifer system, the sodium-adsorption ratio (SAR) generally is less than 2 and has a median value of 0.37. In areas with larger sodium concentrations or a sodium chloride water type, the SAR has been found to be as large as 30; these areas generally are associated with both seawater intrusion and larger concentrations of dissolved solids. Although dissolved solids generally are in the range of 100 to 150 mg/L, larger values in the range of 300 to 500 mg/L are found in the ground water in low-lying areas adjacent to Puget Sound and are often associated with seawater intrusion. Generally, large dissolved-solids concentrations are associated with a sodium chloride water type and small concentrations are associated with calcium bicarbonate and calcium-magnesium bicarbonate types.

Elevated concentrations of iron and manganese are common in the glacial aquifers in the study area. Concentrations of iron and manganese, as much as 2.5 mg/L and 0.65 mg/L, respectively, have been found in the aquifers. Water-sample analyses in some of the coastal areas have shown that manganese can be more abundant than iron, which is atypical of glacial aquifers (Dion and others, 1988). The large differences between the average and median values for dissolved iron and manganese (table 5) indicate the areal distribution of the elevated concentrations.

Concentrations of dissolved nitrate-plus-nitrite (hereafter referred to as nitrate) generally are small in the ground water in the study area; most reported values are less than 1.0 mg/L expressed as nitrogen, and the median nitrate concentration is about 0.1 mg/L (table 5). The order of magnitude of difference between the average and median nitrate indicates that large concentrations of nitrate have been observed locally. Moderate to large concentrations of nitrate have been found in Thurston, Pierce, Skagit, and Whatcom Counties. Larger concentrations in parts of Thurston and Pierce Counties may be due to on-site waste disposal systems in the extensively developed, unsewered residential areas. The larger concentrations found in Skagit and Whatcom Counties, both of which have large agricultural areas, may be due to feedlot wastes or fertilizers. Although Turney (1986) reported a maximum value of nitrate of 9.3 mg/L in Whatcom County, a 1992 study of part of Whatcom County has determined values of more than 40 mg/L in the Fraser aquifer (S.E. Cox, U.S. Geological Survey, written commun., 1993). In this 1992 study of Whatcom County, analyses of samples taken from nested piezometers open to different depths in the Fraser aquifer showed that the highest concentrations were found in the shallow piezometers and that there was a rapid decrease in nitrate concentrations with depth, indicating that the large concentrations were probably due to sources at the land surface. This part of the aquifer system in Whatcom County is contained in the structural Fraser-Whatcom Basin which includes the Fraser Lowland of British Columbia, Canada. Liebscher and others (1992) also found elevated concentrations of nitrate in the part of the Fraser aquifer in British Columbia. Liebscher and others (1992) observed nitrate concentrations in the ground water that were as much as 41 mg/L and showed that large nitrate concentrations generally are site specific, fluctuate seasonally, and are due to land-use activities. Additionally, 12 of 23 pesticides that were sampled for were detected in the ground water.

Table 5.--*Summary of historical ground-water quality data for the Puget Sound and the Willamette Lowland aquifer systems*

[Values are for all regional hydrogeologic units; values in milligrams per liter unless otherwise indicated; cols./100 mL, colonies per 100 milliliters; µg/L, micrograms per liter; --, no data]

Constituent	Average	Median	Number of sample sites
Puget Sound aquifer system			
Specific conductance (microsiemens)	365	180	4,414
pH (standard units)	7.3	7.3	1,905
Bacteria, fecal-coliform (cols./100 mL)	1.2	1.0	1,072
Hardness (as $CaCO_3$)	81	60	1,960
Calcium, dissolved	17	13	1,871
Magnesium, dissolved	8.2	5.9	1,871
Sodium, dissolved	23	6.5	1,735
Sodium-adsorption ratio	1.2	.37	1,699
Potassium, dissolved	2.4	1.8	1,722
Alkalinity, total (as $CaCO_3$)	81	65	1,113
Sulfate, dissolved	9.2	5.0	1,789
Chloride, dissolved	55	4.7	4,371
Silica, dissolved (as SiO_2)	30	29	1,713
Dissolved solids, calculated (sum of constituents)	164	112	1,668
Nitrate plus nitrite (as N), dissolved	1.4	.1	1,117
Iron, dissolved (µg/L)	922	38	1,314
Manganese, dissolved (µg/L)	131	17	1,207
Willamette Lowland aquifer system			
Specific conductance (microsiemens)	401	217	230
pH (standard units)	7.4	7.4	255
Bacteria, fecal-coliform (cols./100 mL)	--	--	--
Hardness (as $CaCO_3$)	--	--	--
Calcium, dissolved	41	19	261
Magnesium, dissolved	9.1	8.1	261
Sodium, dissolved	32	9.5	261
Sodium-adsorption ratio	--	--	--
Potassium, dissolved	2.8	1.7	237
Alkalinity, total (as $CaCO_3$)	--	--	--
Sulfate, dissolved	6.2	2.8	261
Chloride, dissolved	77	4.5	261
Silica, dissolved (as SiO_2)	42	42	258
Dissolved solids, calculated (sum of constituents)	278	171	261
Nitrate plus nitrite (as N), dissolved	--	--	--
Iron, dissolved (µg/L)	575	100	223
Manganese, dissolved (µg/L)	106	30	162

Seawater has intruded both the Fraser and Puget aquifers near the shoreline, most commonly in the island and peninsular areas and near large coastal pumping centers. Water in the aquifer units near the shoreline that are below sea level may contain large concentrations of chloride and show seasonal fluctuations in concentrations in selected locations. Generally, chloride concentration value of more than 100 mg/L is an indicator of seawater intrusion in the Puget Sound Lowland. Seawater intrusion is largest and most prevalent in San Juan and Island Counties due to the small recharge quantities, low topographic relief, and the small lateral extent of the Puget Sound aquifer system.

In summary, the quality of the ground water in the Puget Sound aquifer system is good and suitable for most uses. Larger concentrations of selected constituents can be attributed to locally derived sources. The large quantity of recharge that enters the aquifer system, the generally large values of hydraulic conductivity, and the short flow paths commonly result in a system where general constituent concentrations are nearly vertically homogenous. Proximity to salt water and selected types of bedrock can locally affect the water quality of the ground water. The potentially important water-quality problems are related to seawater intrusion and locally derived sources of nitrogen. However, site specific ground-water contamination has occurred and may continue to occur due to anthropogenic sources. Although rarely a health problem, larger concentrations of iron and manganese in parts of the glacial aquifers may be considered an aesthetic problem.

WILLAMETTE LOWLAND AQUIFER SYSTEM

Geology

By the early Miocene, regional uplift had created a low relief precursor to the Coast Range, which generally restricted marine sedimentation to the western flanks of the Coast Range. At this time, the Willamette Lowland had still not developed to its present form. During the middle Miocene, lava flows of the Columbia River Basalt Group (CRBG) originated from the Columbia Plateau in eastern Oregon and Washington and entered western Oregon. The flows followed the ancestral Columbia River and spread throughout the area as far south as Albany, Oreg. The Miocene Coast Range impeded the westward movement of the lava flows. Tectonic activity increased during late Miocene and Pliocene, resulting in the uplift of the Coast Range and subsidence of the present-day Willamette Lowland, establishing it as a major depositional basin for continental sediments. As a result of the tectonic activity, the CRBG now composes the uplands that separate the four major structural basins (see fig. 11).

Basin-fill sediments were deposited in the Willamette Lowland probably over a considerable period of time. Fossil flora found near the upper surface of the fine-grained sediments in the Portland area indicate an early Pliocene age, and fossil pollen from fine-grained sediments in the southern Willamette Valley indicate a Pliocene-Pleistocene age. These dates suggest that deposition of sediment in the valley started soon after emplacement of the CRBG.

Terrace deposits exist in a few places along the eastern margin and in places along the southern parts of the central Willamette Valley. These deposits of deeply weathered silt, sand, and gravel also exist along the periphery of the southern Willamette Valley. There generally are at least two distinct terrace levels, approximately 50 ft and 100 ft above the present stream level. These older alluvial sediments vary in thickness from a few feet to as much as 200 ft. The presence of these terrace deposits indicates that the rate of tectonism, the rate of sedimentation, and drainage patterns have varied throughout the evolution of the valley (Gannett and Caldwell, in press). Many of these deposits represent remnants of ancient stream channels or alluvial fans at the margins of the valley. These deposits further indicate that evolution of the basin fill has included periods of erosion, at least near the margins.

The structural and erosional basins in the Willamette Lowland have been filled with sediments from a number of sources including the Coast and Cascade Ranges, as well as the Columbia River. The lithology, mineralogy, and grain-size distribution of sediment is different for each of these sources. The proportions of basin-fill sediment from each of these sources have varied with time. The sediment from the Coast Range is predominantly clay, silt, and fine sand derived from weathering and erosion of marine sandstone, siltstone, and shale. Most of the basin-fill sediment in the Tualatin Basin was probably derived from basalts, with some contribution from the Coast Range. Sediment from the Cascade Range is composed entirely of volcanic clasts, and includes a variety of grain sizes. Most of the coarse sand and gravel in southern and central Willamette Valley is from the Cascade Range. The Columbia River sediment generally is restricted to the Portland Basin and includes lithologies exotic to the region such as quartzite, and granitic and metamorphic clasts.

The basin-fill sediments in the Portland Basin are underlain by the CRBG and the basement confining unit. The lower several hundred feet of basin-fill sediment overlying these units in the Portland Basin consists largely of siltstone, mudstone, and claystone. These fine-grained sediments have a maximum thickness in the center of the basin of more than 1,400 ft. However, where the Columbia River enters the basin, sediments in the upper part of the fine-grained section grade laterally into a sequence of sand and gravel. This sand and gravel facies can be considered an interbed within the fine-grained section, and it underlies an area of about 120 mi^2, averages 50 ft thick, and locally is more than 200 ft thick (Swanson and others, 1993). It appears to be thickest near the present channel of the Columbia River. A layer of sand and basaltic conglomerate, averaging 100 to 200 ft thick, occurs in the upper part of the fine-grained section in the southern part of the Portland Basin, thins toward the west and northwest, and grades into fine-grained sediments near the center of the basin.

Overlying the fine-grained sediments in the Portland Basin is a sandstone and conglomerate unit. This unit underlies the entire Portland Basin, averages about 100 to 400 ft in thickness and is as much as 900 ft thick in east Portland. This unit of coarse materials becomes thick toward the east.

Overlying this sandstone and conglomerate unit in the eastern part of the Portland Basin are volcanic conglomerates and mudflows derived from the Cascade Range. These deposits include gravel with interbedded mudflows that locally compose a large part of the unit.

The basin-fill sediments in the Tualatin Basin consist of clay and silt with some sand and a few gravel beds. Analysis of well logs shows at least 1,480 ft of fine-grained sediment in the central part of the Tualatin Basin. These basin-fill sediments overlie the CRBG.

In the central Willamette Valley, the lower part of the basin-fill section overlying the CRBG predominantly consists of fine-grained sediments. These sediments in the northern part of the central valley are siltstone, mudstone, and sandstone; the sediments are coarser grained toward the south, becoming predominantly gravel in the vicinity of Salem. The fine-grained sediments have been described as a thick layer of blue clay and shale separated by layers of sand and fine gravel that generally are less than 5 ft thick. A number of water wells and oil and gas wells penetrate as much as 1,600 ft of fine-grained sediments before reaching the CRBG. These sediments in the central Willamette Valley lack a significant Columbia River facies.

Overlying the fine-grained sediments in the central Willamette Valley is a section of coarse-grained sediments. These sediments in the upper part of the basin-fill section consist of gravel, interlayered sand, and some sandy silt. The most extensive gravels are as alluvial fans.

The stratigraphy of basin-fill sediments in the southern Willamette Valley is similar to that of the central Willamette Valley. However, over most of the southern Willamette Valley, the basin-fill sediments overlie the basement confining unit where the CRBG is not present. Generally, fine-grained fluvial sediments dominate below a depth of about 100 ft. These fine-grained sediments are not as thick as those in the central Willamette Valley but are more than 340 ft thick. These sediments consist of clay to silty clay, sandy clay, and clayey silt, with lenses of well-sorted, unconsolidated medium to fine sand. The sand layers appear to be of limited lateral extent, and compose about 10 to 15 percent of the unit, and are 2 to 4 ft thick. The upper 50 to 100 ft of sediment consists largely of sand and gravel, interbedded with fine sand and silt. These coarse sediments grade down-valley into finer-grained sediments.

The grain-size distribution and geometry of lithofacies within the basin-fill sediment in central and southern Willamette Valley indicate that most gravel has been deposited as alluvial fans formed by streams emanating from the Cascade Range—very little coarse-grained sediment appears to have come out of the Coast Range. Large alluvial fans are associated with the McKenzie, South Santiam, North Santiam, and Molalla Rivers; except the Molalla River, these rivers extend to the glaciated areas of the Cascade Range. Where these major streams enter the valley, sand and gravel deposits 200 to 300 ft thick directly overlie bedrock; these deposits extend up into the valleys of the tributary drainages. In the subsurface, these coarse sediments grade laterally into, and interfinger with, progressively finer sediments toward the valley center. These coarse and fine sediments represent the proximal and distal facies, respectively, of alluvial fans which have probably existed since uplift of the Cascade Range. These large alluvial fans all have modern topographic expression and were last in a major constructional phase during the Pleistocene. The fans are being incised by modern streams.

During the Pleistocene, drainages which included glaciated terrain in the Cascades delivered a large volume of coarse sediment to the Willamette Lowland. The coarse, proximal fan facies protruded out onto the valley floor where they coalesced, probably in a braided river system, to form a laterally mappable gravel unit (Allison, 1953).

This unit is the most extensive, laterally continuous Quaternary gravel deposit in the Willamette Lowland. This unit occurs over much of the southern Willamette Valley near the top of the basin-fill section. This laterally extensive layer of sand and gravel is a few tens of feet thick and corresponds to part of the upper coarse-grained section. Deposits analogous to this unit occur in the uplands along the eastern side of the central Willamette Valley but do not appear to be as continuous on the valley floor. However, where it exists on the valley floor, it also occurs near the top of the basin-fill section, and consists of sand and gravel. Analogous deposits in the Portland Basin have been obscured by late Pleistocene glacial-outburst floods.

Tertiary to Quaternary basaltic and andesitic lavas that occur in the Portland area generally are referred to as the Boring Lava (Treasher, 1942). The Boring Lava occurs in the Portland Basin, on the plateau separating the Portland Basin from the central Willamette Valley, and along the west side of the Tualatin Mountains in the Tualatin Basin. The Boring Lava consists primarily of flows with minor pyroclastic debris that generally exhibit columnar, blocky, or platy jointing. The age of the Boring Lava is believed to be late Pliocene to early Pleistocene.

Numerous Boring Lava eruptive centers occur in the Portland area. These include shield volcanos up to a few miles in diameter and remnants of older cones. Generally, 100 to 200 ft thick, the Boring Lava thickness ranges from about 50 ft in areas far from vents to more than 600 ft near vents (Beeson and others, 1989).

Late Pleistocene glacial-outburst floods, originating in the upper Columbia River Basin, deposited a variety of sediments in the Willamette Lowland. The thickness and grain size of these sediments generally decrease with distance from the eastern extent of the Portland Basin.

In the Portland Basin, flood sediments that blanket the basin floor consist largely of unconsolidated gravel and sand. The deposits in the Portland, Oreg. area and east of Vancouver, Wash. are composed predominantly of bouldery pebble and cobble gravel with a sand matrix. A sandy phase grades north and west into silty and clayey material. Sandy deposits have also been mapped in west Portland. The thickness of the flood sediments in the Portland Basin varies due to pre-flood topography and post- flood erosion. The flood sediments are as much as 250 ft thick, but generally range from less than 100 ft to about 150 ft.

Flood sediments in the Tualatin Basin generally consist of silt with some clay. The silt averages 60 to 90 ft thick throughout much of the basin, and has a maximum thickness of about 120 ft.

The flood sediments in the central and southern Willamette Valleys are named the Willamette Silt (fig. 10) and generally are silt and very fine sand. These sediments occur up to an altitude of about 350 to 400 ft in the central Willamette Valley, but they are not a mappable unit above an altitude of about 325 ft. The sediments have a maximum thickness of about 130 ft near the middle of the central Willamette Valley and thin toward the margins. In the southern Willamette Valley, the flood sediments are much thinner than in the central Willamette Valley. The Willamette Silt is 9 to 13 ft thick in the type section about 10 mi south of Corvallis, Oreg., and averages about 15 ft thick at Albany, Oreg.

Holocene alluvium is present in the flood plains of all major streams in the Willamette Lowland. The lithology and thickness of the alluvium varies areally. In the southern Willamette Valley, it is predominantly sand and gravel and averages a few tens of feet thick; in about 10 percent of the area, it contains sufficient silt and clay to limit permeability. In the central Willamette Valley, the alluvium generally consists of sand and gravel along major streams entering the valley from the Cascade foothills. The alluvium consists primarily of sand-to-clay size material along smaller streams. The alluvium along the Willamette River consists of sand and gravel in the central Willamette Valley and becomes progressively finer grained and thicker downstream. In the Portland area, alluvium along the Willamette and Columbia Rivers consists primarily of sand and silt that generally is less than 50 ft thick but locally is as much as 100 ft thick. Alluvium along the major tributaries in the Portland Basin generally is sand and gravel. In the Tualatin Basin, the alluvium is fine grained, consisting of fine sand, silt, clay, and peaty material.

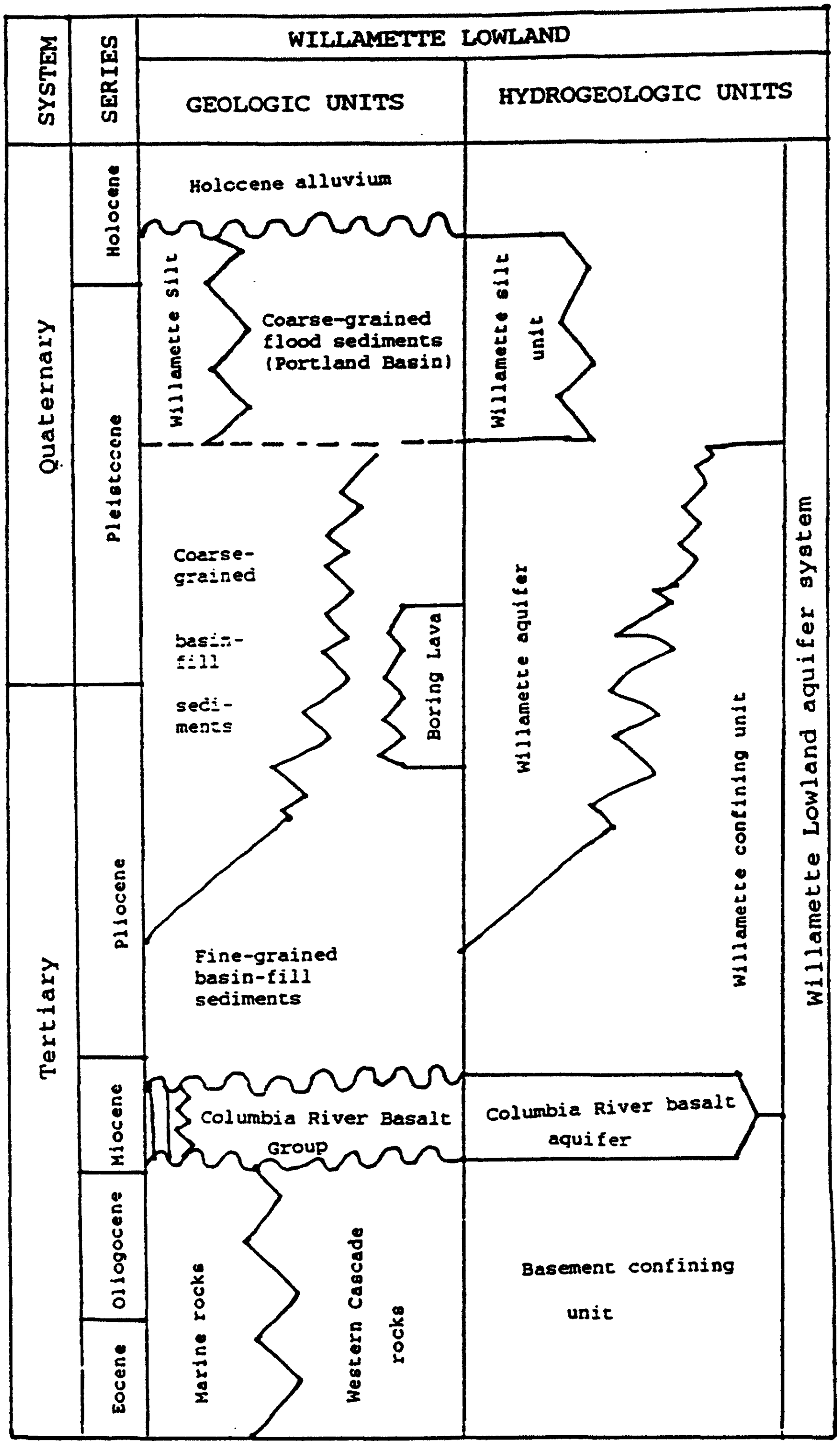


Figure 10.--Correlation chart showing the regional relation between generalized geologic units and hydrogeologic units for the Willamette Lowland aquifer system. From Gannett and Caldwell (in press) and Woodward and others (in press).

Hydrogeologic Units

The regional hydrogeologic units defined for the Willamette Lowland aquifer system are composed of one or more of the geologic units that have similar hydrogeologic characteristics and are adjacent or occupy similar stratigraphic positions. The geologic units are composed of the CRBG, basin-fill sediments, glacial-outburst flood sediments, and Holocene alluvium which, in turn, compose aquifer units and semiconfining-to-confining units. The aquifer units consist of basalt and coarse-grained deposits, and the other units consist of fine-grained deposits.

Five regional hydrogeologic units have been defined for the Willamette Lowland (Gannett and Caldwell, in press). These units are, from oldest to youngest, the basement confining unit, the Columbia River basalt aquifer (composed of the CRBG), the Willamette confining unit (composed of the fine-grained basin-fill sediments), the Willamette aquifer (predominantly composed of the coarse-grained basin-fill sediments), and the Willamette silt unit (predominantly composed of the Willamette Silt). A correlation chart showing the relation between the hydrogeologic units and the generalized geologic units is presented on figure 10, and the generalized lateral extent of the surficial regional hydrogeologic units is shown on figure 11. Because a number of wells yield water from the Boring Lava, its extent is shown on figure 11 and it is presented in the correlation chart (fig. 10). However, the formation generally is limited in extent, and where it is the most extensive, it overlies the Willamette confining unit. Thus, it was not defined as one of the regional hydrogeologic units for this study. Maps of the extent of the hydrogeologic units are presented in Gannett and Caldwell (in press) and in Woodward and others (in press).

The basement confining unit forms the lateral and basal boundaries of the aquifer system and includes all of the geologic units that underlie either the CRBG or basin-fill sediments. The units include the Tertiary marine sediments and Eocene volcanics of the Coast Range, and the volcanics of the western Cascade Range. Tertiary marine sandstone, siltstone, claystone, and shale underlie most of southern and central Willamette Valley, the entire Tualatin Basin, and the western part of the Portland Basin. Marine sediments and western Cascade volcanic rocks underlie the eastern parts of southern and central Willamette Valley. Additionally, about 179 mi^2 of small, isolated or discontinuous areas with basin-fill sediments were aggregated with the basement-confining unit.

The Columbia River basalt aquifer is the largest and most lithologically uniform hydrogeologic unit in the study area. The Columbia River basalt aquifer underlies approximately 2,600 mi^2 of the northern part of the Willamette Lowland. The Columbia River basalt aquifer is the uppermost hydrogeologic unit over about 580 mi^2 (fig. 11), mostly in upland areas where it is an important source of water. It is locally exposed in foothills adjacent to southern and central Willamette Valley, the Portland Basin, and the Tualatin Basin. The unit averages a few hundred to several hundreds of feet thick, but is as much as 2,000 ft thick south of the Tualatin Basin. Because very few wells penetrate through the entire Columbia River basalt aquifer, there was not sufficient information available to produce a detailed map of its thickness during this study. About 2,000 mi^2 of the unit is overlain by basin-fill sediments in the central Willamette Valley, the Tualatin Basin, and most of the Portland Basin.

The hydrology of the CRBG in north central Oregon and central Washington has been extensively described by Hansen and others (1994) for a previous RASA study, and its hydrology is the same as that of the Columbia River basalt aquifer. The aquifer generally consists of multiple individual lava flows 10 to 100 ft thick, averaging about 50 ft thick. The interflow zones between successive lava flows often include the brecciated, vesicular top of one flow, possible sedimentary interbeds, and the rubbly base of the overlying flow. These interflow zones are, in places, very porous and highly permeable and generally have relatively large horizontal conductivity. Flow centers usually consist of dense basalt cut by numerous cooling joints, which generally are vertically-oriented. These joints may be tightly closed or not interconnected. Therefore, vertical conductivity of the flow centers generally is much smaller than horizontal conductivity of the interflow zones; the low conductivity of the flow centers restricts the movement of water into and between the water-producing interflow zones.

The Willamette confining unit consists of the fine-grained sediments in the lower part of the basin-fill section. The unit is considered a regional confining unit because of its extent and generally small conductivity (table 2). The Willamette confining unit underlies about 3,000 mi^2 of the aquifer system, and it is volumetrically the largest within the basin-fill sequence. The unit is the surficial hydrogeologic unit over about 225 mi^2.

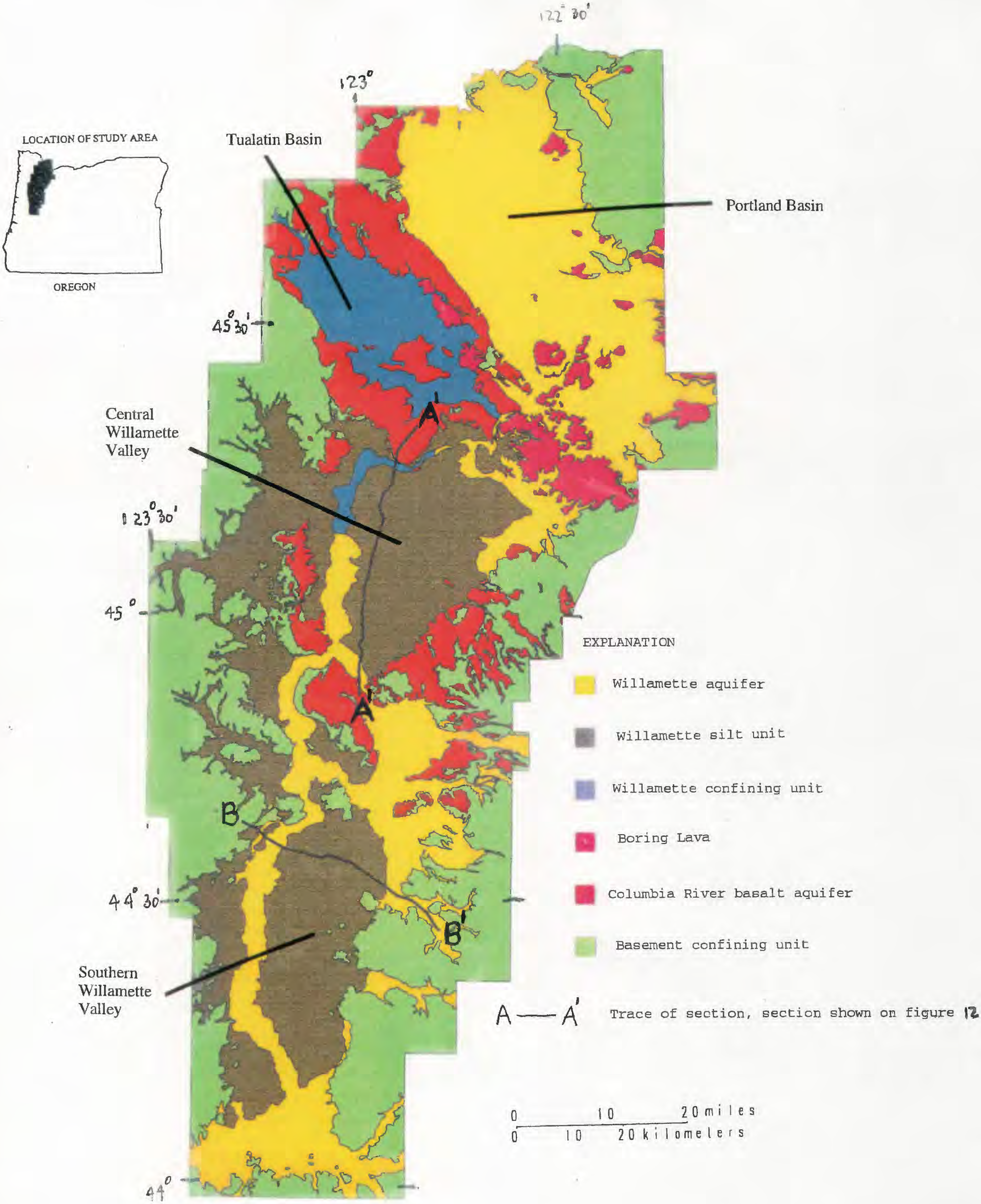


Figure 11.--Generalized extent of surficial regional hydrogeologic units and the Boring Lava for the Willamette Lowland aquifer system, and location of major structural basins. From Woodward and others (in press).

The top of the Willamette confining unit generally reflects the facies boundary between coarse-grained and fine-grained basin-fill sediments. Low areas occur in the top of the Willamette confining unit where coarse-grained alluvial fan facies dominate the basin-fill section. In the Tualatin Basin, all of the basin-fill sediments, including the glacial-outburst flood sediments, are considered part of the Willamette confining unit. Therefore, the top of the unit is land surface.

The thickness of the Willamette confining unit ranges from less than 100 ft to more than 1,600 ft. The unit is thickest in the central parts of the central Willamette Valley, the Tualatin Basin, and the Portland Basin. Averaging 100 ft to 300 ft thick, the unit is thinner in the southern Willamette Valley and along the periphery of the Willamette Lowland. Thickness contours of the Willamette confining unit resemble altitude contours of the bottom of the basin-fill sediments because the quantity of relief on the top of the basement confining unit and Columbia River basalt aquifer is much larger than the relief on the top of the Willamette confining unit (Gannett and Caldwell, in press).

The Willamette confining unit locally contains sand or gravel interbeds that serve as aquifers. These interbeds generally are thin and not laterally continuous. However, there are some areas where potentially productive sand and gravel interbeds are known to occur within the Willamette confining unit. For example, in the central Willamette Valley, a tongue-shaped interbed of sand and gravel about 10 to 30 ft thick extends several miles north from the Salem, Oreg., area; this interbed locally is an important aquifer. Additionally, there is an extensive gravel interbed within the Willamette confining unit in the Portland Basin, which underlies an area of 120 mi^2

The Willamette aquifer is the principal aquifer in the Willamette Lowland aquifer system. The unit occurs over 2,500 mi^2 and ranges from less than 20 ft to more than 600 ft thick. It is the surficial hydrogeologic unit over about 1,640 mi^2. The Willamette aquifer consists primarily of layers of sand and gravel that are a few to several tens of feet thick with interbeds of sand, silt, and clay. The fine-grained interbeds are thinner and fewer in number than their coarse-grained counterparts.

In the Portland Basin, the Willamette aquifer includes most of the coarse-grained basin-fill sediments above the fine-grained sediments composing the Willamette confining unit. The Willamette aquifer also includes glacial-outburst flood sediments, glacial outwash, and Holocene alluvial deposits.

The top of the Willamette aquifer in the Portland Basin is land surface. In southern and central Willamette Valley, the top of the unit resembles the surface topography; it is essentially the pre-flood land surface. Large alluvial fans are readily apparent where the McKenzie, South Santiam, North Santiam, and Molalla Rivers enter the Willamette Lowland. Fan morphology is not apparent in the Portland Basin because the Columbia River has aggraded due to world-wide sea-level rise since the Pleistocene, obscuring some of the Pleistocene topography.

The thickness of the Willamette aquifer in the southern and central Willamette Valleys ranges from 140 to 300 ft, and the thickest parts are coincident with the large alluvial fans. The Willamette aquifer is much thinner (averaging only about 20 to 40 ft thick) and locally discontinuous between the alluvial fans. The gravel between the fans generally occurs at or near the top of the pre-flood basin-fill section. In the southern Willamette Valley, this gravel corresponds to the laterally extensive gravel unit described previously. Floodwaters entering the central Willamette Valley near Oregon City, Oreg., had sufficient velocity to transport gravel, which was deposited as a small gravel fan that grades into the Willamette Silt. Because of its lithology, this gravel is included in the Willamette aquifer. In the Portland Basin, the Willamette aquifer averages from 100 to 400 ft thick and locally is more than 600 ft thick. The large thickness is due to both the large sediment source of the Columbia River and the inclusion of glacial-outburst flood sediments in the unit.

In the central Willamette Valley, the Mount Angel Fault Zone has had a major influence on the facies distribution within the basin-fill sediments and the geometry of the Willamette aquifer. The Willamette aquifer is much thicker on the south side of this structure and thins abruptly across the fault zone to the north. More rapid subsidence of the basin on the south side probably localized drainages in that area during basin development.

The Willamette silt unit includes the fine-grained deposits above the Willamette aquifer. The unit overlies about 1,220 mi^2 in the central and southern Willamette Valley, where it is the surficial hydrogeologic unit. The unit forms a wedge-shaped deposit that thins toward the south. The Willamette silt unit consists predominantly of the Willamette Silt, which has a uniform lithology over the entire area outside of the Portland Basin. Above an altitude of about 325 ft on the valley floor, the Willamette Silt cannot be distinguished from other fine-grained surficial deposits and recent alluvium on the modern Willamette River floodplain. The mapped Willamette silt unit includes some pre-flood sands and silts of local fluvial origin, in addition to the flood-depositional sediment. In the Tualatin Basin, where the Willamette aquifer does not occur, the flood-deposited silt is considered part of the Willamette confining unit.

The Willamette silt unit is as much as 130 ft thick in the middle part of the central Willamette Valley and thins to about 10 ft thick in the southern Willamette Valley. The unit has been generally eroded in the present flood plains of the Willamette River and its major tributaries. The Willamette silt unit is partly saturated in most places on the valley floor; the water table is in the unit over much of its extent. However, the unit generally is not used as a source of water and is considered a regional semiconfining-to-confining unit.

The Willamette Lowland aquifer system consists of two aquifer units—the Columbia River basalt aquifer and the Willamette aquifer, and two semiconfining-to-confining units—the Willamette confining unit and the Willamette silt unit. The basement confining unit forms the lateral and basal boundary of the aquifer system. Hydrogeologic sections showing typical distributions of units within the Willamette Lowland aquifer system are shown on figure 12, and table 1 presents information on the physical dimensions of the aquifer system and the units that compose the system.

Hydraulic Conductivity

The ranges in horizontal hydraulic conductivity for the regional hydrogeologic units are presented in table 2. As with the Puget Sound aquifer system, a large range in values is due to the variations in lithology, consolidation, and cementation of the deposits. The large range in reported values for the Willamette aquifer (0.03 to 7,000 ft/d; table 2) is primarily due to the large variations of grain-size distributions associated with the different geologic units that compose the aquifer, the presence of fine-grained deposits, and the contribution of the semi-consolidated to consolidated and partly cemented sand and gravel parts of the aquifer. These parts are associated with older geologic units. Generally, the upper part of the Willamette aquifer has conductivities that range from about 100 to 1,000 ft/d, whereas the older and generally deeper part of the aquifer has conductivities that range from about 1 to 100 ft/d. The larger values typically are for Holocene alluvium, buried gravel-dominated alluvial fans, coarse-grained Columbia River and outburst-flood deposits, and reworked flood plain deposits. The latter, smaller values generally correspond to older, cemented gravels, sandstone, and semi-consolidated, cemented sand and gravel deposits. Median values of hydraulic conductivities for the Willamette aquifer range from about 50 to 75 ft/d.

Hydraulic conductivity values for the Columbia River basalt aquifer generally range from about 0.001 to 750 ft/d (table 2). The large range is due to the physical setting (geologic structure) and number of interflow zones encountered by wells used to estimate the conductivity. For example, in relatively flat topography where vertical gradients are upward, a deep well may have a larger apparent conductivity than a well of the same depth completed in an upland where the vertical gradient is downward, and the dip of the basalts flows is large. The effective conductivities for both of these types of areas also could be greatly increased or decreased depending on the number of interflow zones that are present, and for estimating conductivity, the number of zones that the well bore is open to. Additionally, Hansen and others (1994) also indicated that deformation of the CRBG, such as in anticlines (typically expressed as uplands), not only may result in the juxtapositioning of the interflow zones (which support most of the lateral flow) but also appears to close connected pore space. On the basis of the analyses of Hansen and others (1994) and Morgan and McFarland (1994), median conductivities for the undeformed and for the structurally affected basalts are about 1 to 3 ft/d and about 0.01 to 0.1 ft/d, respectively.

Wells that withdraw water from the Willamette confining unit generally are completed in coarse-grained zones contained locally in this unit. Available hydraulic conductivity data for this unit are representative of those zones, and are not typical of the unit as a whole. However, by calculating hydraulic conductivity values from 113 specific-capacity tests for wells completed in productive zones in this unit in the Portland Basin, Morgan and McFarland (1994) found that values ranged from about 0.01 to 90 ft/d (table 2), and averaged about 2 ft/d. The average value indicates that the Willamette confining unit in the Portland Basin is composed of fine-grained sediments, but also includes silty sands. Throughout the remainder of the aquifer system, the unit contains a diverse assemblage of fine-grained sediments with some interbedded coarse-grained sediments. On the basis of the results of two cross-sectional flow models (Woodward and others, in press), the unit probably has an average conductivity of about 1 ft/d in the remaining areas. The range and average are much larger than those for the generally clayey, confining unit of the Puget Sound aquifer system. However, with respect to the Willamette aquifer, the conductivity of the Willamette confining unit is about one to two orders of magnitude smaller, which characterizes it as

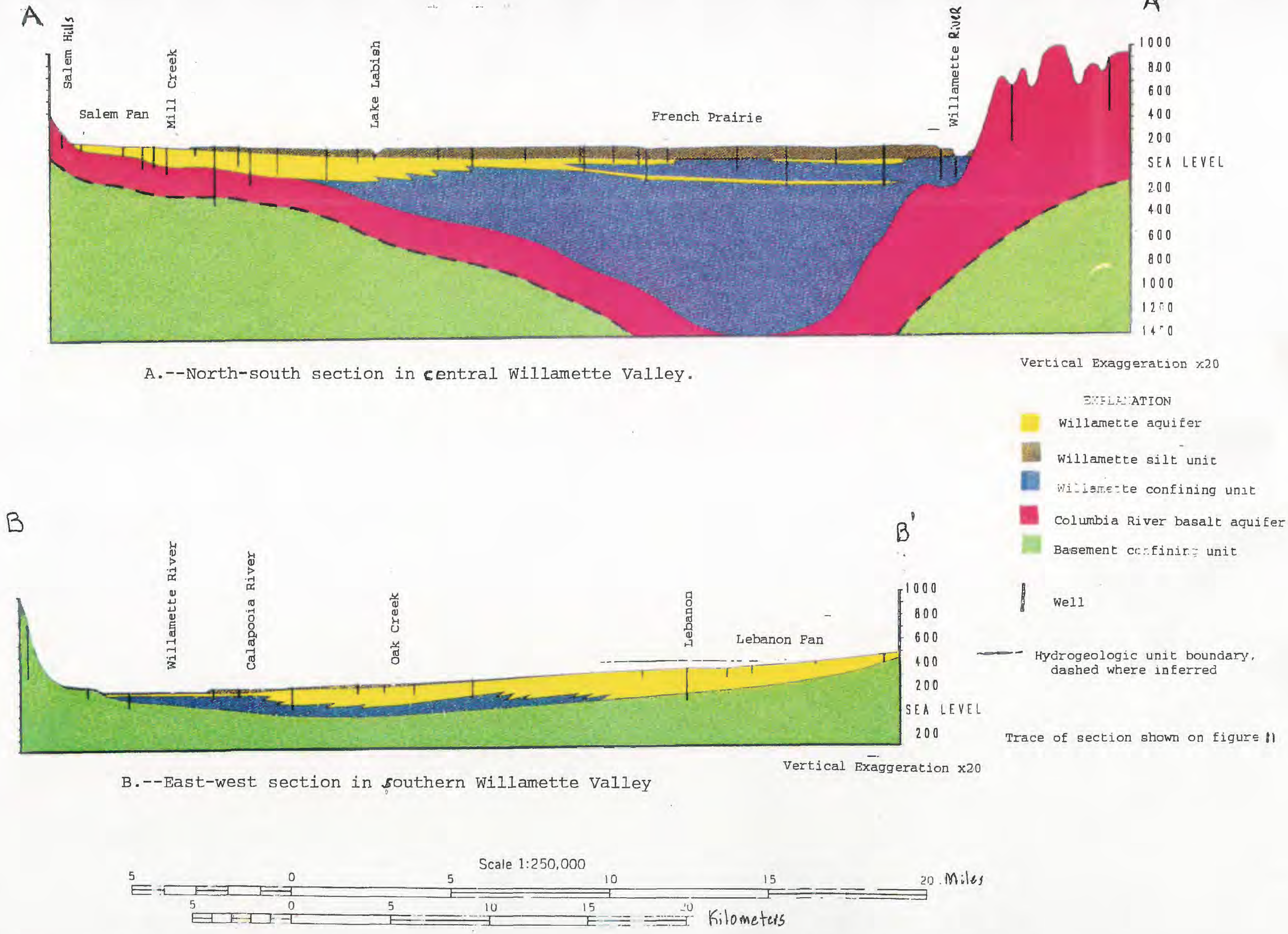


Figure12.--Hydrogeologic sections for the Willamette Lowland aquifer system. From Gannett and Caldwell (in press) and Woodward and others (in press).

a confining unit. For example, Woodward and others (in press) describe saline water contained in the marine sediments as confined due to the small hydraulic conductivity of the Willamette confining unit. They also show that saline water may intrude the Willamette aquifer where the confining unit is thin or absent. A median value of about 1 ft/d appears to be a reasonable estimate for the hydraulic conductivity of the Willamette confining unit.

Although the water table is in the Willamette silt unit over much of its extent, the unit generally is not used as an aquifer. Therefore, there are no field tests for hydraulic-conductivity data for this unit. On the basis of its lithologic character, and Price's (1967) laboratory analyses of cores, values of conductivity for this unit probably range from about 0.01 to 8 ft/d (table 2). Additionally, the potential for the latter, larger values is supported by the lack of drainage networks over part of this unit, which indicates the unit is permeable enough to allow for the percolation of relatively large quantities of precipitation. Using a value of 1 ft/d for this unit in the two cross-sectional flow models resulted in calculated vertical head gradients that were similar to the observed gradients. Therefore, as with the Willamette confining unit, a median hydraulic conductivity value of about 1 ft/d appears to be a reasonable estimate for the Willamette silt unit.

Ground-Water Recharge

Mean annual ground-water recharge to the Willamette Lowland aquifer system was estimated on the basis of derived relations between recharge and the mean annual precipitation, types of surficial materials (areas covered by basalt, coarse-grained deposits, and fine-grained deposits) and land use and land-cover (Woodward and others, in press). The basalt-covered areas correspond to the surficial extent of the Columbia River basalt aquifer and the Boring Lava; the coarse-grain covered areas correspond to the flood plain deposits of the Willamette aquifer; and the fine-grain covered areas correspond to the remaining part of the Willamette aquifer, the Willamette confining unit, and the Willamette silt unit. Additionally, estimates were also derived for about 179 mi^2 of coarse- and fine-grained deposits which were included as part of the basement confining unit. The relations were derived on the basis of the results of daily water-budget models (Snyder and others, 1994; Bauer and Vaccaro, 1990) and on the analysis of the response of water-levels to precipitation (Woodward and others, in press). Mean annual recharge was first estimated on the basis of three relations (one for each category of surficial geology) between mean annual precipitation to recharge. The estimated recharge was then reduced on the basis of land use and land-cover. Estimates of ground-water recharge derived by Snyder and others (1994) for most of the Portland Basin were then substituted in place of the above estimates for that area.

Mean annual recharge to the Willamette Lowland aquifer system was estimated to be19.3 in/yr or 5,463 ft^3/s (about 3,800,000 acre-ft of water—41 percent of the total precipitation) (table 3). These estimates include about a 1.1 in/yr or 279 ft^3/s reduction in recharge due to land use and land-cover effects. Mean annual recharge was estimated to be about 20.7 in/yr (1,126 ft^3/s) to the basalts, 21.4 in/yr (1,244 ft^3/s) to the coarse-grain covered areas, and 18.1 in/yr (3,093 ft^3/s) to the fine-grain covered areas. These quantities represent 40, 49, and 39 percent of the precipitation falling on each of the categories, respectively. Mean annual unit recharge to the aquifer system is about 1.42 $ft^3/s/mi^2$. The estimate of mean annual recharge to the aquifer system is about 16 percent of the mean annual flow of the Willamette River and about 63 percent of the mean August flow. If the quantity of recharge in Clark County, Wash. is excluded, these two percentages are slightly reduced. The estimated spatial distribution of mean annual recharge is shown on figure 13, and the results of the analyses are presented in table 3.

Low (August) and high (June) seepage measurements conducted in 1993 on the Willamette River by the U.S. Geological Survey showed large differences in river gains between these two periods (A. Laenen, U.S. Geological Survey, written commun., 1993; Woodward and others, in press). The total gain from ground-water, as calculated for the river reach up to the gaging station for the Willamette River at Salem, Oreg., was about 100 ft^3/s for the August flows and about 2,300 ft^3/s for the June flows. Correspondingly, ground-water level hydrographs show rising water levels from about October-November to about February, nearly constant water levels from February to March, and declining water levels from about April to September. The results of the seepage measurements and ground-water level hydrographs together indicate that the mean annual estimate of ground-water recharge is reasonable (Woodward and others, in press).

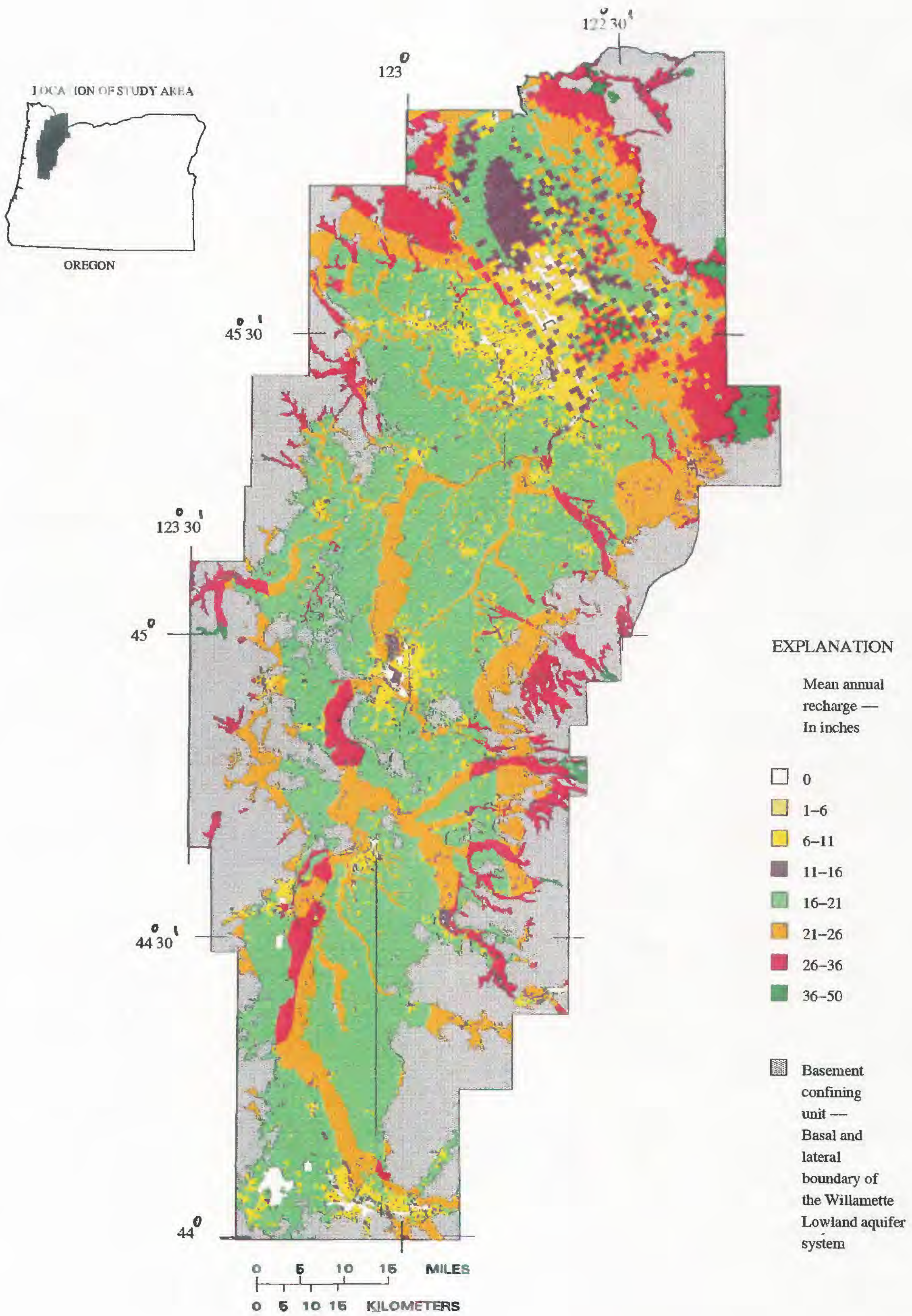


Figure 13.--Estimated distribution of mean annual ground-water recharge for the Willamette Lowland aquifer system. From Woodward and others (in press).

The estimated recharge quantities for the different categories of surficial geology are similar to those for the Puget Sound aquifer system for areas where the annual precipitation quantities are similar. However, the spatial variability of precipitation and recharge in the Willamette Lowland is much less than that in the Puget Sound Lowland; much of the Willamette Lowland receives about 40 in/yr of precipitation. The smaller spatial variability can be seen by comparing the estimated spatial distribution of recharge shown on figures 8 and 13. The potential interannual variability of this spatial variability in recharge for the three surficial geologic categories also was estimated by using 102 years of water-year precipitation data for a weather site at Corvallis, Oreg. (mean annual precipitation of about 40.4 in/yr). During this period (1890-1991), water-year precipitation varied from about 24 to 68 in/yr. Recharge was estimated to range from 7.96 to 28.8 in/yr for the basalt areas, from 14.6 to 39.3 in/yr for coarse-grain covered areas, and from 10.5 to 28.4 in/yr for fine-grain covered areas. The smallest water-year recharge values were estimated to occur in 1977 and the largest in 1974, the water years with the smallest and largest total precipitation. Correspondingly, the lowest and highest annual flows (9,760 ft^3/s and 38,000 ft^3/s) for the Willamette River at Salem, Oreg., occurred during these two years. The results indicate the potential for large interannual variations in recharge to the Willamette Lowland aquifer system.

Ground-Water Flow System

Regional ground-water movement generally is from the uplands toward the major rivers, particularly the Willamette and Columbia Rivers. The direction of movement is predominantly horizontal in the Willamette aquifer and both horizontal and vertical in the Columbia River basalt aquifer. Vertical gradients generally are small in the Willamette aquifer and large in the Columbia River basalt aquifer; most vertical gradients are downward in the uplands and upward near streams. Where the aquifer units are exposed at land surface, ground water is unconfined. Ground water in the Willamette aquifer tends to be semiconfined to confined where the aquifer is overlain by the Willamette silt unit, which is saturated over much of its extent (the water table is in this unit in those areas). In the uplands where there are large downward vertical gradients, water in the Columbia River basalt aquifer is unconfined at shallow depths and is semiconfined at successively deeper interflow zones. Where the vertical gradient becomes upward (near the periphery of the valley floors), ground water is confined.

Movement of water in the aquifer system is controlled by topography, geometry of the aquifer system, hydraulic conductivity, ground-water recharge, ground water-surface water hydraulic connections, and location of discharge areas. The generalized direction of ground-water flow for the unconsolidated deposits composing the aquifer system shown on figure 14 indicates certain aspects of those controls, which are described below.

Topographic control generally is related to short flow paths. The horizontal hydraulic gradient may be large in these areas of short paths. Longer flow paths indicate the subregional flow paths, which also may be affected by topography; if they are affected, land surface generally slopes towards the terminus of the flow path (the discharge location) without intervening hills or ridges. Along longer flow paths, most of the recharge discharges locally in local flow systems in the upper part of the system. Where the geometry of the aquifer system changes, the movement of ground water also changes. For example, abrupt thinning of the Willamette aquifer results in increased horizontal gradients, and where the aquifer terminates against basalt, flow paths also terminate (or begin). Hydraulic conductivity largely controls the rate of water than can move along any flow path; this control generally is expressed as either steepening or flattening of the horizontal gradient. Because of the relatively uniform and large quantity of recharge, its control is not easily discerned from the pattern of movement. Generally, the recharge quantities largely determine the quantity of water that can move in the system and the net ground-water availability. Additionally, seasonal fluctuations in water levels (which range from about 3 to as much as 30 ft) are controlled by recharge. Ground water-surface water connections are expressed as upgradient water-level contour flexures (ground-water flows to the stream) or downgradient contour flexures (streams lose water to the aquifer). The former is the dominant flow pattern in the aquifer system. The latter occurs where the rivers entering the lowlands from the Cascade Range first cross the large buried alluvial fans. The regional and local discharge locations occur where all flow paths terminate. In the Willamette Lowland aquifer system, these locations are at major rivers. Thus, discharge locations and ground water-surface water connections are closely related. Selected aspects of the above discussion are described below on the basis of mapped ground-water levels and the results of two cross-sectional ground-water flow models (Woodward and others, in press).

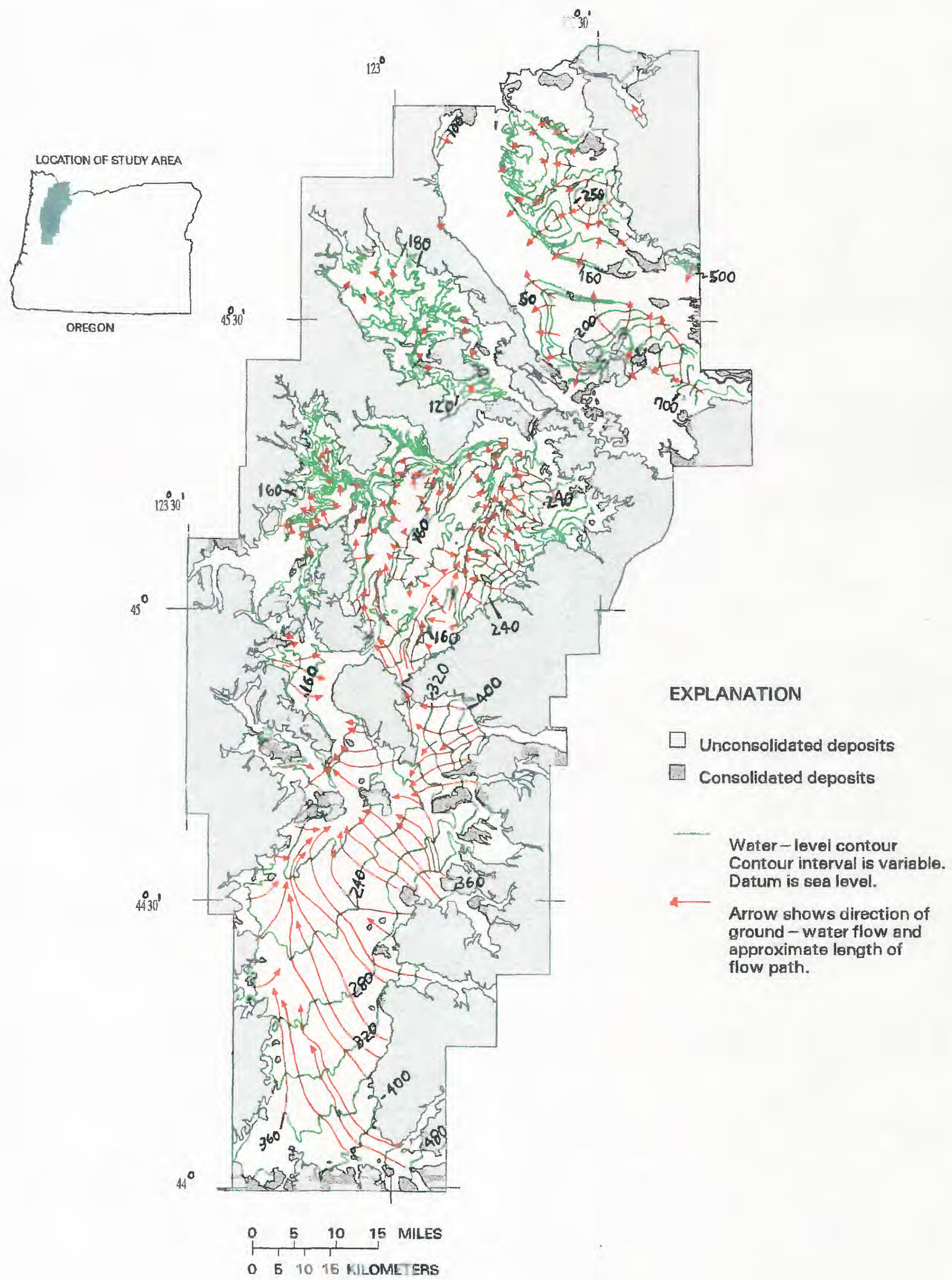


Figure 14.--Generalized pattern of ground-water movement for the unconsolidated deposits, Willamette Lowland aquifer system. Lateral hydraulic gradients are indicated by spacing of generalized water-level contours. Detailed water-level contours presented in Woodward and others (in press).

Lengths of ground-water flow paths range from about 2,000 ft in the upper, peripheral parts of the aquifer system to as much as 40 mi in the deeper parts of the system and in the southern Willamette Valley. No flow paths extend the length of the aquifer system, principally due to the control of geologic structure and secondarily due to the control of surface-water bodies. Generally, the flow paths define four generally isolated subregional flow systems (one within each of the four basins), especially within the Willamette aquifer.

There is a distinct variation in topographic control and the length of the flow paths for each basin. The southern Willamette Valley typically has long flow paths that define a relatively broad system. Most flow-path lengths range from 5 to 15 mi, and maximum lengths range from 30 to 40 mi. The dominant flow direction is from the east to the west-northwest. In the central Willamette Valley, flow-path lengths generally range from 3 to 5 mi, and maximum lengths are about 10 mi. The control of topography is shown by the pattern of ground-water movement (fig. 14). The flow pattern and lengths of flow paths in the Tualatin Basin are similar to those in parts of the central Willamette Valley. However, because the structural basin is smaller, most of the flow paths are about 2 to 5 mi in length. In the Portland Basin, flow-path lengths range from about 1 to 10 mi; the longer flow paths occur in Clark County, Wash., where the topography is more uniform than south of the Columbia River.

Horizontal hydraulic gradients in the Willamette aquifer range from about 2 ft/mi (0.0004 ft/ft) to about 60 ft/mi (0.01 ft/ft). The smaller gradients generally are found in the flood plain of the Willamette River where the topography is flat and the reworked sediments are nearly all coarse—the fine-grained components have been transported out of the system. The larger gradients are found in the uplands and in areas with large topographic relief. Throughout most of the Willamette aquifer, horizontal gradients average 10 to 40 ft/mi (0.002 to 0.008 ft/ft). Generally, the smallest gradients occur in the southern Willamette Valley, where the gradients average about 13 ft/mi (0.002 ft/ft); gradients range from about 0.0004 ft/ft in the flood plains to about 0.004 ft/ft in the uplands and in the area near Stayton, Oreg. The gradient in the central Willamette Valley generally ranges from 14 to 200 ft/mi (0.003 to 0.04 ft/ft) and averages 40 ft/mi (0.008 ft/ft). The horizontal gradient in the Tualatin Basin generally is larger than in central and southern Willamette Valley, and it averages 50 ft/mi (0.01 ft/ft). Gradients in the Portland Basin range from 5 to 50 ft/mi (0.001 to 0.01 ft/ft) and average 30 ft/mi (0.006 ft/ft).

Horizontal gradients in the Columbia River basalt aquifer generally parallel the dip slope of the basalts. This correspondence between the slope of the basalt flow and the horizontal gradient also was observed for the CRBG in the RASA study of the Columbia Plateau aquifer system (Whiteman, 1986). Thus, horizontal gradients are large in the uplands where the aquifer is exposed, and the gradients are smaller where the aquifer underlies the valley floors of the Tualatin Basin, the central Willamette Valley, and the Portland Basin.

Horizontal gradients in the Columbia River basalt aquifer also are affected by faults. Generally, gradients steepen near faults attributed to the juxtaposition of interflow zones with less permeable flow centers. This steepening of gradients also has been noted in the Willamette aquifer along a line in southwestern Clark County, Wash. (Morgan and McFarland, 1994). Although the present-day configuration of the basement confining unit was established prior to the filling of the lowland with basin-fill sediments, the coincidence of the steepening with an underlying anticline suggests that some post-Pliocene tectonic activity has occurred in this area.

Vertical hydraulic gradients in the Willamette aquifer generally are small and range from 0.02 to 0.30 ft/ft. The largest gradients generally are found in the uplands, especially where the unit is thick, and along erosional features such as bluffs. The smallest gradients generally occur on the valley floors where the Willamette silt unit is absent. Most vertical gradients are downward in the Willamette aquifer and change to upward near the major streams. Vertical head differences that are associated with the gradients range from 5 to 60 ft. Larger head differences are found where the aquifer is thick and there are more interbedded layers of fine-grained sediments. For example, Morgan and McFarland (1994) found that the fine-grained sediments, where they are extensive, can have a large control on the flow system in the Portland Basin.

Vertical gradients in the Columbia River basalt aquifer generally are larger than in the Willamette aquifer. Gradients typically are 0.3 to 0.5 ft/ft. Most vertical gradients are downward except near discharge areas, which generally are located in topographic lows. The transition from downward to upward gradients generally is abrupt and occurs near the periphery of the valley floors. Flowing wells in the Columbia River basalt aquifer are common along the edges of the valley floors. Geologic structure also affects vertical gradients. Where subregional to regional flow is downward locally, faults not only impede lateral movement but also induce vertically upward flow.

As ground water moves from topographic highs toward the rivers in the lowlands, about 60 to 70 percent of the recharge discharges in local flow systems (Morgan and McFarland, 1994; Woodward and others, in press). For example, of the estimated 1,800 ft^3/s of recharge in the Portland Basin, about 1,200 ft^3/s was estimated to discharge in local flow systems (Morgan and McFarland, 1994). Depending on the physical setting, the local flow systems may also be equivalent to the terminal part of the subregional or regional flow system.

Water Use

The largest ground-water uses in the Willamette Lowland are, from smallest to largest, public supply, industrial, and irrigation. Ground-water use generally has increased as both population and irrigated acreage have increased. Previous estimates of ground-water use were compiled for different parts of the Willamette Lowland for different years, from 1955-75 (Woodward and others, in press). In 1970, ground-water pumpage was about 340 Mgal/d (381,000 acre-ft). Of these withdrawals, 15 percent was for public supply, about 40 percent was for industrial use, and about 45 percent was for irrigation. Additionally, about 50 percent of the irrigation withdrawals occurred in the southern Willamette Valley. Correspondingly, about 30 percent of the total withdrawals occurred in the southern Willamette Valley, and 54 percent occurred in the Portland Basin where industrial use was largest.

As part of a large-scale study of the ground-water resources of the Portland Basin and as part of this RASA study, Collins and Broad (1994; 1996) estimated the areal distribution of ground-water withdrawals for the entire aquifer system. Aggregated into three categories (public supply, industrial supply, and irrigation supply), the estimates were for 1990. Collins and Broad (1996) estimated that about 300 Mgal/d (336,250 acre-ft; 465 ft^3/s) of ground water was withdrawn for all uses (table 4). The distribution and quantity of these withdrawals show that most of the withdrawals occurred in the central Willamette Valley.

Public supply withdrawals in 1990 were about 62 Mgal/d (69,600 acre-ft; 96 ft^3/s) (table 4). Of this quantity, about 56 percent was withdrawn in the Portland Basin. About 34 percent of the total was withdrawn by the City of Vancouver, Wash., in the Portland Basin. About 17 and 22 percent of the public supply withdrawals occurred in the central and southern Willamette Valleys, respectively. Only about 5 percent of the total public supply was withdrawn in the Tualatin Basin.

Industrial withdrawals were estimated for about 120 wells and totaled about 64 Mgal/d (72,150 acre-ft; 100 ft^3/s) (table 4). About 92 percent of these withdrawals in 1990 occurred in the Portland Basin. The large quantity of industrial withdrawals in the Portland Basin corresponds to the clustering of industry along the Columbia River in both Oregon and Washington, particularly, in Portland, Oreg., and Vancouver, Wash.

Withdrawals for irrigation in 1990 were estimated to be about 174 Mgal/d (194,500 acre-ft; 269 ft^3/s) (table 4) and were pumped from about 8,100 irrigation wells. About 57 percent (98 Mgal/d) of the water was pumped from the central Willamette Valley and about 37 percent (65 Mgal/d) from the southern Willamette Valley. Irrigation withdrawals account for about 58 percent of the total withdrawals from the aquifer system (table 4).

From 1955-90, the use, distribution, and quantity of withdrawals has changed. In areas of large population growth, such as the Portland Basin, irrigation withdrawals have declined and public supply withdrawals have increased. As in the Puget Sound Lowland, industrial use has greatly decreased due to the conversion and diversification of the economic base of the Willamette Lowland, mainly in reduced wood processing, milling, and paper manufacturing activities. The acreage of ground-water irrigated lands in the central Willamette Valley has largely increased, while the use of ground water for irrigation in the southern Willamette Valley has changed only slightly. Although total withdrawals appeared to have declined from 1955-90, mainly due to reductions in industrial supply, the percent of water supplied from ground-water sources has been increasing, compared with the quantity supplied from surface-water sources.

Ground-Water Quality

The historical ground-water quality data for selected constituents for the Willamette Lowland aquifer system are summarized in table 5. The data are published information from previous investigators (Woodward and others, in press). In comparison to those of the Puget Sound aquifer system, the number of analyses and sample sites is very small.

The dominant water types are calcium-magnesium bicarbonate, sodium-bicarbonate, calcium-sodium chloride, and calcium-magnesium chloride. Each of these water types is associated with a particular geologic unit and also with location within a hydrogeologic unit. Water in the Columbia River basalt aquifer generally is a calcium-magnesium bicarbonate type; in a few locations, it is a calcium-sodium chloride water type. The former is representative of younger water types and the latter of more evolved, older water types. That is, the former type is found in upgradient and recharge areas, and the latter type is found downgradient and deeper in the basalt aquifer. Ground water in the Willamette aquifer generally is a calcium-magnesium bicarbonate type. However, water in a few areas has a calcium-magnesium chloride water type.

Water types of the Tertiary marine sediments of the basement confining unit were estimated (Woodward and others, in press). Of the 38 water samples, 27 had a chloride-dominant type, and the remainder had either a sodium-bicarbonate or calcium-magnesium bicarbonate type. The latter two types generally were found in water samples from wells less than 100 ft deep. The chloride-dominant type was found in water from either deep wells or wells drilled near major faults. Saline connate water contained in the deeper Tertiary marine sediments are confined, with a dominant vertical upward flow component. Similar to water in the marine sediments, a chloride-dominant water type is found in samples from wells in the Columbia River basalt aquifer where the wells are deep or located near major faults. The few (7) samples of a chloride-dominant water type in the Willamette aquifer represent mixing of upward-flowing water (from either marine sediments or the Columbia River basalt aquifer) with water in the Willamette aquifer.

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