HYDROGEOLOGIC FRAMEWORK OF THE WILLAMETTE LOWLAND AQUIFER SYSTEM, OREGON AND WASHINGTON

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ABSTRACT

The Willamette Lowland in Oregon and Washington encompasses 3,700 square miles and includes the low-lying parts of the Willamette Valley in Oregon and most of Clark County, Washington. About 70 percent of the population of Oregon and Clark County, Washington, reside in the Willamette Lowland, and the burgeoning population is increasing the demand for available water. The lowland is 145 miles long and averages 10 to 15 miles in width. Outcrops of folded and faulted basalt within the Willamette Valley divide the lowland into four separate areas or structural basins—from north to south, the Portland Basin, the Tualatin Basin, the central Willamette Valley, and the southern Willamette Valley. Each of these areas has decidedly different hydrologic and hydrogeologic properties.

The 3,700-square-mile aquifer system within the Willamette Lowland is composed of five hydrogeologic units, from oldest to youngest: (1) the basement confining unit, (2) the Columbia River basalt aquifer, (3) the Willamette confining unit, (4) the Willamette aquifer, and (5) the Willamette Silt unit. The Willamette aquifer, the principal aquifer unit in the Willamette Lowland, consists primarily of coarse-grained proximal alluvial-fan and braided-stream deposits. The greatest thicknesses and coarsest materials of the Willamette aquifer outside of the Portland Basin occur in six major alluvial fans that were deposited where major streams from the Cascade Range enter the Willamette Lowland.

The aquifer system in each basin, although hydraulically connected through a series of restrictive water gaps, is distinctive. The Columbia River basalt aquifer and the Willamette confining unit underlie most of the Portland Basin; the Willamette aquifer includes the basin-filling deposits above the Willamette confining unit. The Columbia River basalt aquifer and the Willamette confining unit are the only regional hydrogeologic units above the basement confining unit in the Tualatin Basin.

All five hydrogeologic units occur in the central Willamette Valley. The Columbia River basalt aquifer underlies the entire central Willamette Valley, except for small areas along the far eastern margin, where it thins out against the underlying basement confining unit. A number of faults have been mapped in the central Willamette Valley, some of which offset the aquifer, and numerous other faults have been mapped in the uplands surrounding the basin where the aquifer crops out. The Willamette aquifer in the central Willamette Valley contains three major alluvial fans—the Salem fan, the Molalla fan, and the Canby fan. The Willamette Silt unit overlies most of the central Willamette Valley, has a maximum thickness of about 130 feet near the center of the basin, and generally thins toward the south and near the margins of the basin.

In the southern Willamette Valley, all of the regional hydrogeologic units are present; however, the Columbia River basalt aquifer occurs only in the Stayton Subbasin. The Willamette confining unit is thinner in the southern Willamette Valley than elsewhere in the Willamette Lowland. The Willamette aquifer contains the Lebanon fan and the Stayton fan. The Willamette aquifer is much thinner (averaging only about 20 to 40 feet thick) between the alluvial fans of the southern Willamette Valley than in the central Willamette Valley. The Willamette Silt unit covers most of the southern Willamette Valley and generally thins toward the south.

Ground water in the Willamette aquifer generally occurs under unconfined conditions. The regional water-table map shows an overall pattern of ground-water flow to the major streams, indicating that the base flow of these streams is sustained by ground-water discharge. The hydraulic gradient of the Willamette aquifer ranges from more than 60 feet per mile near the western part of the central Willamette Valley to less than 2 feet per mile in the flood plain of the Willamette River north of Salem, Oregon. On the basis of average values of the hydraulic gradient and the hydraulic characteristics of the Willamette aquifer, the velocity of water moving through the aquifer ranges from 3 to 30 feet per day, which is typical for sand and gravel aquifers.

Long-term hydrographs for observation wells completed in the Willamette aquifer confirm that, on a regional basis, the aquifer is in equilibrium. Water is recharged to the Willamette Lowland aquifer system primarily through the direct infiltration of precipitation on the lowland. An analysis of ground-water recharge from precipitation done for this study showed that about 21,346 ft^3/s (cubic feet per second) of precipitation falls in the study area, of which about 13,186 ft^3/s falls on the aquifer system. Of the latter quantity, about 5,462 ft^3/s is estimated to recharge the aquifer system. The regional estimate of mean annual recharge is about 42 percent of the mean annual precipitation and includes a 280 ft^3/s reduction due to land-use and land-cover effects. Excluding recharge derived from sources other than precipitation, recharge varies seasonally from about 0.05 inches per month in the summer to about 3 to 6 inches per month in the winter. Because most of the low streamflow (during August) in the Willamette River is accounted for by streams entering the lowland, the mean annual recharge helps support base flow from about December through July.

Water is discharged from the Willamette Lowland aquifer system primarily by flow to surface-water bodies (streams, reservoirs, and springs) but also by evapotranspiration and by pumpage through wells. Regionally, ground water flows toward streams and is discharged to the streams through springs and seeps. This ground-water discharge fully supports the base flow of streams that head in the lowland and partially supports the base flow of the other streams. Low-flow discharge measurements were made during August to September 1992 on the Willamette, McKenzie, and Santiam Rivers, and high-flow discharge measurements were made during June and September 1993 on the Willamette River to determine minimum ground-water seepage

into and out of the rivers. The seepage estimates suggest that as streams cross the proximal part of the buried alluvial fans, they lose water to the aquifer, but as the streams cross the distal part of the fans, they gain water from the aquifer.

A considerable volume of ground water in the Willamette Lowland is discharged by evapotranspiration from both the soil root zone and the aquifer system in areas where the water table is near the land surface. On the basis of the results of the cross-sectional ground-water flow models, from 15 to 16 inches per year of evapotranspiration is supported by the aquifer system.

Throughout the Willamette Lowland, an estimated 464 ft^3/s of ground water was withdrawn in 1990 for all uses. For comparison, this quantity is about 4 percent of the mean annual precipitation falling on the aquifer system, about 1 percent of the mean annual flow of the Willamette River, and about 8 percent of the estimated mean annual recharge to the aquifer system.

Most of the shallow ground water throughout the Willamette Lowland is of good chemical quality and is suitable for most uses. Median values of all constituents and properties for the samples from the Columbia River basalt and the Willamette aquifers are similar, although maximum concentrations of calcium, sodium, and chloride are more than 10 times higher in the samples from the Columbia River basalt aquifer, and maximum concentrations of bicarbonate and sulfate are at least 2 times higher in the samples from the Willamette aquifer. On the basis of 75 water samples, ground water in the Columbia River basalt aquifer is predominantly a calcium-magnesium-bicarbonate type, but a few samples were a calcium-sodium-chloride water type. Ground water in the Willamette aquifer, on the basis of 181 analyses, is homogeneous and is predominantly a calcium-magnesium-bicarbonate type, although a few samples are a chloride-dominant (calcium-magnesium-chloride) type.

The occurrence of saline (chloride-dominant) ground water in the Willamette Valley has caused problems and has caused speculation regarding its origin for many years. This study suggests that saline ground water in the lowland is marine connate water, exists at depths in Tertiary marine rocks, and migrates upward along faults and compact folds. The saline water in the Willamette aquifer and Columbia River basalt aquifer, as well as the more dilute chloride-dominant ground water in shallow marine rocks, generally occurs near faults or folds and results from the mixing of shallow meteoric water with deep connate water brought near the surface along the fault zones.

INTRODUCTION

The U.S. Geological Survey began 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 and Johnston, 1994). The regional aquifer systems contained in the Puget-Willamette Lowland were selected to be studied as part of the RASA program (Vaccaro, 1992).

The Puget-Willamette Lowland is located in western Washington, western Oregon, and a small part of southwestern British Columbia, Canada. The study area is contained within a structural (forearc) basin that extends from near the Fraser River, British Columbia, Canada, at about 49 degrees, 15 minutes latitude, to just south of Eugene, Oregon, at about 44 degrees latitude. The Puget-Willamette Lowland study area includes about 23,290 mi^2 (square miles) and is composed of two distinct Neogene sedimentary basins or areas—the Puget Sound Lowland and the Willamette Lowland—separated by bedrock uplands.

The study area for this report is the Willamette Lowland in Oregon and Washington, which encompasses about 5,680 mi^2 and includes the low-lying parts of the Willamette River drainage in Oregon (referred to as the Willamette Valley) and most of Clark County, Washington (fig. 1). The aquifer system within the Willamette Lowland is named the Willamette Lowland aquifer system, and the lateral extent of the principal aquifer units is defined by the area underlain by Recent alluvium, Pliocene to Pleistocene basin-fill sediments and volcanics, and upper Tertiary volcanics. The areal extent of the aquifer system is about 3,700 mi^2.

About 70 percent of the population of Oregon and all of the population of Clark County, Washington, reside in the Willamette Lowland, and the burgeoning population is increasing the demand for available water. In some areas, available water supplies are already fully appropriated, and water supplies are limited by contamination from anthropogenic sources and by saline ground water.

Interpretive results of the Puget-Willamette Lowland RASA study are presented in U.S. Geological Survey Professional Paper 1424, which consists of four chapters. Chapter A describes the geologic framework of the Willamette Lowland (Gannett and Caldwell, 1998); Chapter B (this report) describes the hydrogeologic framework, including results of cross-sectional, ground-water flow modeling of the Willamette Lowland aquifer system; Chapter C describes the geologic framework of the Puget Sound Lowland (Jones, in press); and Chapter D describes the hydrogeologic framework, including results of cross-sectional, ground-water flow modeling of the Puget Sound aquifer system (Vaccaro and others, 1998).

PURPOSE AND APPROACH

This report describes and delineates the hydrogeologic framework of the regional aquifer system in the Willamette Lowland. Most of the data used in this study were compiled from a variety of existing reports and files. Additionally, a field inventory of large-capacity wells provided additional information on 922 areally distributed wells.

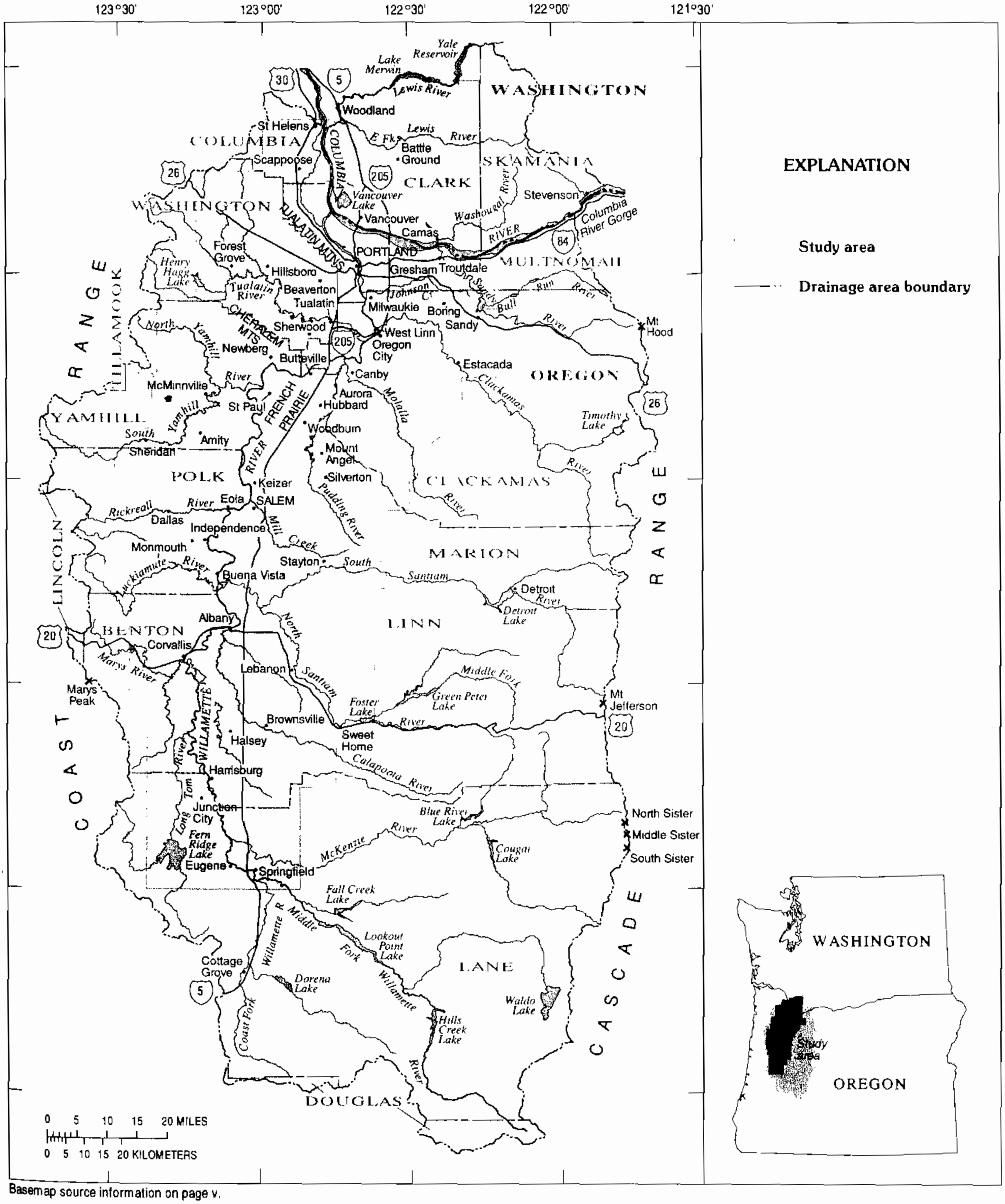

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FIGURE 1.—Outline of the study area with major geographic features in the Willamette River drainage basin, Oregon, and adjacent drainages in southwestern Washington.

The U.S. Weather Bureau (1964) estimated the areal distribution of mean annual precipitation for the entire Willamette Valley, using data from 1930–57. More recently, Daly and Neilson (1992) used data from 1961–90 and an objective precipitation distribution model called Precipitation-elevation Regressions on Independent Slopes Model (PRISM) to estimate precipitation for the valley. PRISM establishes a conceptual framework that allows the quantification and generalization of orographic processes across the landscape and is, thus, particularly suited for areas in or adjacent to mountainous terrain. For this reason, and because more recent precipitation data were used, the isohyetal map used for this study is based on results from PRISM for the Willamette Valley and on U.S. Weather Bureau (1965) mapping for Clark County, Washington.

Regional hydrogeologic units in this report were delineated by Gannett and Caldwell (1998) through interpretation and correlation of lithologic-stratigraphic information from more than 3,000 field-located water wells, oil-test wells, and geotechnical borings. This subsurface information was supplemented by proprietary petroleum seismic data. Detailed surficial geologic maps were used to establish the lateral extent of the hydrogeologic units and major fault trends.

Analysis of water-level hydrographs established that throughout the lowland, long-term trends in the fluctuation of the water table were minimal. Therefore, seasonally consistent altitudes of the water table, measured throughout a span of several years, were used to construct a generalized map of the water table. Water-level measurements for the monthly period, generally from August through October, were used to delineate "low" water-level conditions that were not affected by the winter-spring recharge slug.

Estimates of mean annual recharge to the aquifer system were derived on the basis of results from previous investigations, the distribution of the mean annual precipitation, the surficial extent of the mapped hydrogeologic units, and the digital land-use and land-cover data. Four units categorizing surficial hydrogeologic conditions were defined and their lateral extents were identified. Mean annual precipitation was estimated for each of the units by quantifying the area of each unit that was located within the precipitation contours. The percentage of precipitation that becomes recharge was then estimated on the basis of results from previous studies, and that percentage was then used to estimate recharge for two of the hydrogeologic units. A linear regression equation was used to estimate recharge to a third unit, a basalt unit. Recharge was not estimated for the fourth unit, a bedrock unit. These initial estimated values for recharge were then reduced for selected land-use and land-cover categories. For one large area, detailed estimates of recharge derived by Snyder and others (1994) were used in place of this study's estimates.

Data for the major ground-water uses—public supply, industrial, and irrigation—were compiled, collected, and analyzed on the basis of previous studies, field inventories, and remote-sensing analyses (Collins and Broad, 1996). Analysis of State water-rights data indicate that (1) about 8,100 agricultural irrigation wells are permitted to withdraw about 6,440 acre-ft/d (acre-feet per day) during the irrigation season, (2) about 700 public-supply wells are permitted to withdraw about 2,825 acre-ft/d, and (3) about 500 industrial wells are permitted to withdraw about 770 acre-ft/d. Typically, not all of the permitted wells are in use, and the maximum allowable withdrawals are not being pumped; however, a total of 9,300 permitted wells provides an indication of the number of large-capacity wells in the study area. In order to provide an areally distributed, representative sampling of these wells, a detailed field inventory was conducted during the summer and fall of 1990; detailed information on well location and construction, water level, pumping rate, water use, and irrigated acreage and crop type was collected for 705 irrigation wells, 135 public-supply wells, and 122 industrial wells.

Satellite imagery, consisting of Landsat Thematic Mapper digital data, was interpreted and ultimately classified to delineate irrigated acreage in the central part of the study area between Oregon City and Albany, Oregon (fig. 1). State water-rights data were used to determine the percentage of total irrigated acreage supplied by ground water (as opposed to that percentage supplied by surface water) for each square-mile section in the lowland. This percentage was multiplied by the irrigated acreage delineated from the satellite imagery to derive an estimate of acreage irrigated with ground water on a section-by-section basis. This value was then multiplied by the locally adjusted crop-application water rate to compute an estimated volume of ground water withdrawn for irrigation. These data then were aggregated on a quarter-township basis for presentation on maps.

Hydraulic characteristics of the individual aquifer units were determined by a literature search of previously published data and by calculations that were made using information contained in Federal and State data bases. Specific-capacity values were calculated separately for comparison, and the values were then used to estimate transmissivity.

An overview of the chemical quality of ground water is based on the characterization of 314 analyses of water samples previously collected throughout the study area. The samples were aggregated into three groups for comparison and analysis.

GEOGRAPHIC SETTING

Native Americans were attracted to the Willamette Valley because of the mild climate and an abundance of game, water, and trees. Captain William Clark, co-leader of the Lewis and Clark Expedition, wrote in his journal on April 3, 1806, that "the Cal-lar-poe-wah Indian Nation are very numerous and inhabit the country on each side of the Multnomar [present-day Willamette River] from its falls as far up as the knowledge of those people extend" (Thwaites, 1904). The settlement of the Willamette Lowland by non-Indians began in 1825 when Dr. John McLoughlin moved his Hudson Bay Company headquarters to Fort Vancouver, a site on the north bank of the Columbia River at the present location of the city of Vancouver, Washington. The Willamette River and its tributaries offered readily available transportation and domestic water supplies. By 1836, the first permanent settlement in the Willamette Valley was situated along the river in the French Prairie area, between the present cities of Salem and Portland, Oregon; and by 1850, the French Prairie settlers numbered approximately 1,200 (Loy, 1976). The long growing season enabled the cultivation of a variety of crops, and the level to gently rolling terrain was relatively easy to farm. The Oregon Territorial Census indicated that the total population of the Willamette Valley was 11,631 in 1850; most of the settlers lived in towns along the rivers.

Steamboats first appeared on the Willamette River in 1850, and regular riverboat traffic extended between Portland and Eugene, Oregon, by 1856. Portland gradually became the dominant city in the region. The Oregon Territory gained Statehood in 1859, accompanied by renewed growth in the valley. By 1871, railroads linked Portland and Eugene on both sides of the valley and opened up large tracts of farmland that formerly were not accessible to river commerce. Completion of the transcontinental railroad in the 1880's was a turning point in the Oregon economy; at last there was access to a national market for local products. Timber and timber products gradually increased in importance.

As of the mid 1990's, the economy of the area is based on a diversity of industries, including agriculture, manufacturing, and service. The wet and mild October through May climatic regime is conducive to the winter growth of crops such as grain, grass, and legume seed, which mature uniformly and produce quality seed during the dry summer. The combination of a favorable climate and an abundant supply of high-quality water have been the major factors in the rapid development of a food-processing industry in the Willamette Valley; as a result, the Willamette Valley ranks as one of the largest fruit and vegetable processing areas in the Nation (Pacific Northwest River Basins Commission, 1971b). In addition, many communities in the study area rely on the timber and wood-products industries.

According to the 1990 census, approximately 70 percent of the 2,842,000 people in Oregon live in the Willamette Valley and an additional 238,000 people live in Clark County, Washington; thus, about 2,230,000 people reside in the Willamette Lowland study area. Between 1950 and 1990, the population in the study area more than doubled (from 1,100,000 to 2,230,000). The fastest growth took place between 1960–70 and between 1970–80, when the rate of growth for each decade was about 25 percent.

LOCATION AND EXTENT

The Willamette Lowland, the southern extension of the Puget-Willamette Lowland, is a north-south-oriented, structural and topographic depression that is bounded on the north and east by the Cascade Range, on the west by the Coast Range, and on the south by an upland where the two mountain ranges merge (fig. 1). The Willamette Valley in Oregon comprises about 90 percent of the lowland, and the remaining 10 percent is located north of the Columbia River in Clark County, Washington. The Willamette Lowland is drained primarily by the northward-flowing Willamette River in the Willamette Valley and by the Lewis River in Clark County; additionally, the Columbia River crosses the northern part of the lowland and is the major trunk river in the region (fig. 1).

The principal regional aquifer in the Willamette Lowland consists of permeable basin-fill sediments that underlie the lowland. As a result, the study area for the Willamette Lowland part of the RASA study consists of the contiguous low-altitude, low-relief topographic area in the lowland and the adjacent flanks of the surrounding mountains (fig. 1). Only the lower reaches of the flat-lying alluvial valleys associated with drainages tributary to the Willamette River are included in the study area. The study area covers about 5,680 mi^2, of which about 5,045 mi^2 is in the Willamette Valley and 635 mi^2 is in Clark County, Washington.

PHYSIOGRAPHY AND SOILS OF THE LOWLAND

The Willamette Lowland is about 145 mi (miles) long and averages about 10 to 15 mi in width; the altitude of the lowland ranges from about 450 ft (feet) above sea level at the southern end to near sea level at the Columbia River. Outcrops of folded and faulted basalt divide the lowland into four separate areas or structural basins—from north to south, the Portland Basin (Oregon and Washington), the Tualatin Basin (Oregon), the central Willamette Valley (Oregon), and the southern Willamette Valley (Oregon) (fig. 2). Each of these areas has decidedly different hydrologic and hydrogeologic properties.

The Willamette Basin, the structural basin that contains the Willamette Lowland, is asymmetric in cross section (fig. 3a) because of the emplacement mode and composition of rocks composing the Coast and Cascade Ranges. The Coast Range is composed primarily of folded marine sedimentary rocks (shale and sandstone) that crest no more than about 2,500 ft above sea level. Scattered igneous rocks, however, form isolated peaks that range in elevation from about 3,400 ft to a high of 4,097 ft at Mary's Peak west of Corvallis, Oregon. In contrast, the Cascade Range is composed almost entirely of volcanic rocks that crest between 4,000 and 6,500 ft above sea level. The Cascade Range also contains many peaks higher than 8,000 ft, including five volcanic peaks ranging in altitude from 10,047 to 11,235 ft above sea level along the crest of the Cascade Range (fig. 1). These peaks were subject to Pleistocene alpine glaciation and retain perennial glaciers to this day.

The Willamette Lowland has a low-altitude, low-relief surface that is incised by perennial and intermittent streams that drain the adjacent mountains and the valley. Perennial streams extend into the adjacent bedrock and have well-defined, broad valleys that are larger than the present streams require, whereas intermittent streams do not cut into adjacent bedrock and usually occupy only narrow, vertical-walled channels in the center of broad swales (Glenn, 1965). Balster and Parsons (1968) defined and mapped nine separate geomorphic surfaces within the Willamette Valley. For the purposes of this report, only two major surfaces will be discussed—the lowland surface (top of basin-fill sediments, typically, the top of the Willamette Silt) and the flood plain (top of Quaternary alluvium) (fig. 3b).

The lowland generally slopes to the northwest throughout most of the valley, primarily because of extensive alluvial fans deposited by major rivers that drain the high Cascade Range east of the valley. As a result of this topography, the present course of the Willamette River and its flood plain is near the western margin of the valley. The lowland surface coincides with the top of a geologic unit, the Willamette Silt, throughout the study area except for the Portland Basin and the extreme southern part where this silt was not deposited. Steep, near-vertical bluffs composed of the Willamette Silt separate the flood-plain surface from the lowland surface; the relief of the bluffs increases in a downstream direction and ranges from about 0 ft near Harrisburg, Oregon, where the two surfaces merge, to about 80 ft near Wilsonville, Oregon (fig. 3b).

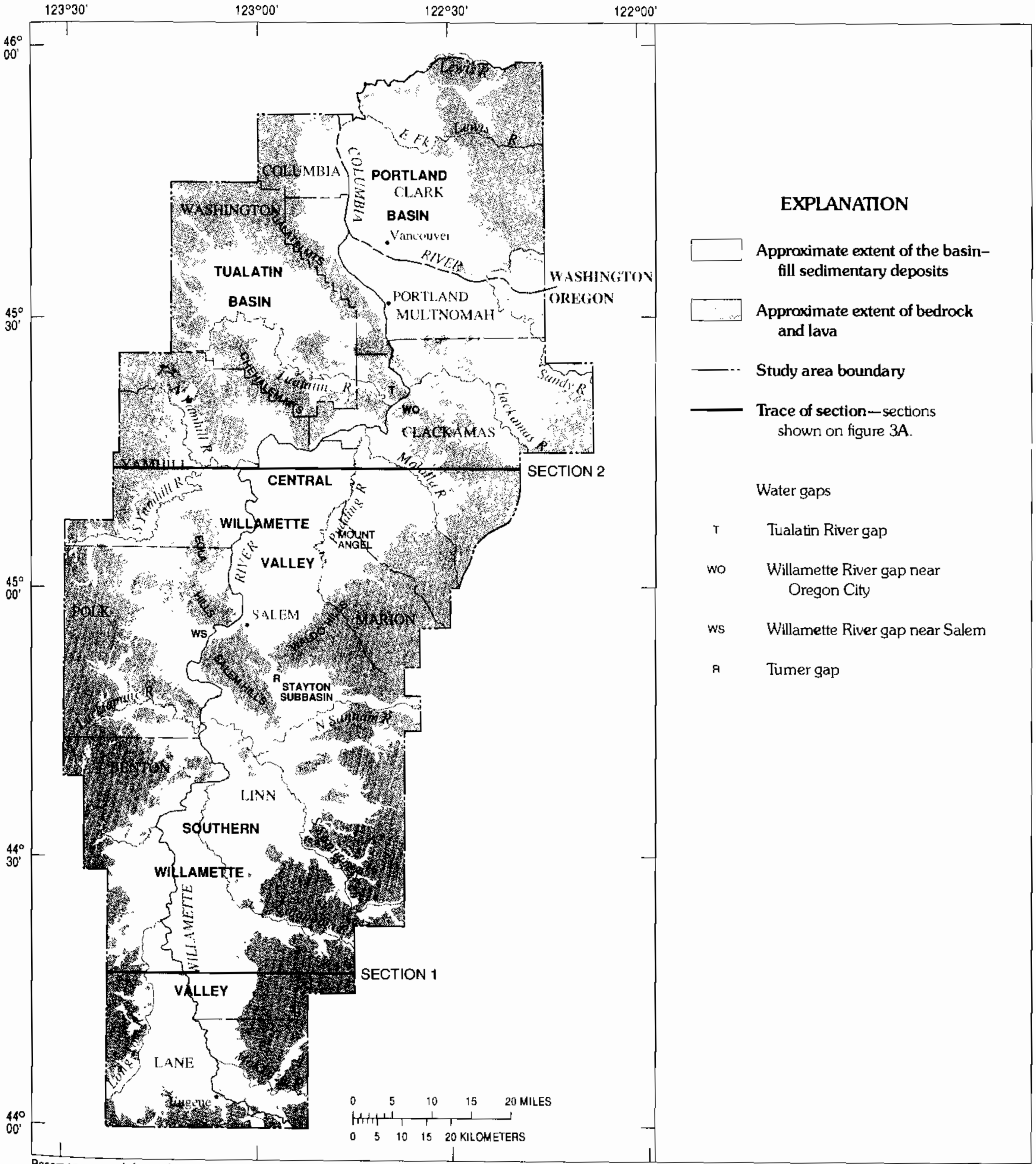
Most of the 187-mile channel of the Willamette River is braided or meandering and flows through a flood plain that ranges from about 0.5 to 4 mi wide. The flood plain contains irregular alluvial terraces and is characterized by many cutoff meanders, oxbow lakes, braided and distributing channels, and sloughs. The flood plain generally slopes at about the same rate as the Willamette River, except for the reach downstream from Salem, Oregon, where the slope is less than that of the river (fig. 3b).

The lowest flood-plain surface of the Willamette River is underlain by coarse or moderately coarse alluvium (Balster and Parsons, 1968). Sand and gravel removal is common at many locations along the flood plain, in the main channel of the Willamette River, and in the lower reaches of many of its tributaries; the sand and gravel has been a principal source for construction aggregates for many decades (Klingeman, 1973). A minimum-draft navigation channel has been maintained over the years by the U.S. Army Corps of Engineers as far upstream as Albany, Oregon, and the dredged gravel generally has been spoiled along the river banks (Klingeman, 1973).

Clark County, Washington, which constitutes the northeastern part of the Willamette Lowland, is bounded on the south and west by the Columbia River and is drained by streams that are tributary to that river (fig. 1). The eastern half of the county is composed of volcanic foothills along the western flank of the Cascade Range; the foothills contain peaks as high as 4,000 ft above sea level, but peaks with altitudes between 2,000 and 3,000 ft are more common. Faulting and glaciation in the foothills area have affected the topography and drainage patterns in the county (Mundorff, 1964).

The western half of Clark County is a lowland consisting of a series of flat-lying plains and terraces that rise from the Columbia River at an altitude of a few feet above sea level to about 800 ft. The highest terrace—locally called the Troutdale bench, the Fifth Plain, or the Highland Area—is from 2 to 7 mi wide and is separated from the lower plains by a scarp 100 to 200 ft high. Most of the lowland in Clark County occurs on a broad fill terrace—locally called the Fourth Plain—that is about 300 ft above sea level. This fill terrace consists of coalescing alluvial fans deposited by the Columbia River and its tributaries that drain the foothills in the county (Mundorff, 1964).

Soils in the lowlands generally are silty and sandy and have a subsoil structure that allows for rapid infiltration, which tends to prevent surface runoff (Pacific Northwest River Basins Commission, 1970a). Soils in the modern flood plain are silty loams or silty clay loams, with a soil depth of more than 5 ft.



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Geologic data modified from Gannett and Caldwell, 1998, USGS Professional Paper 1424-A.

FIGURE 2.—Location of Willamette Lowland and structural basins.

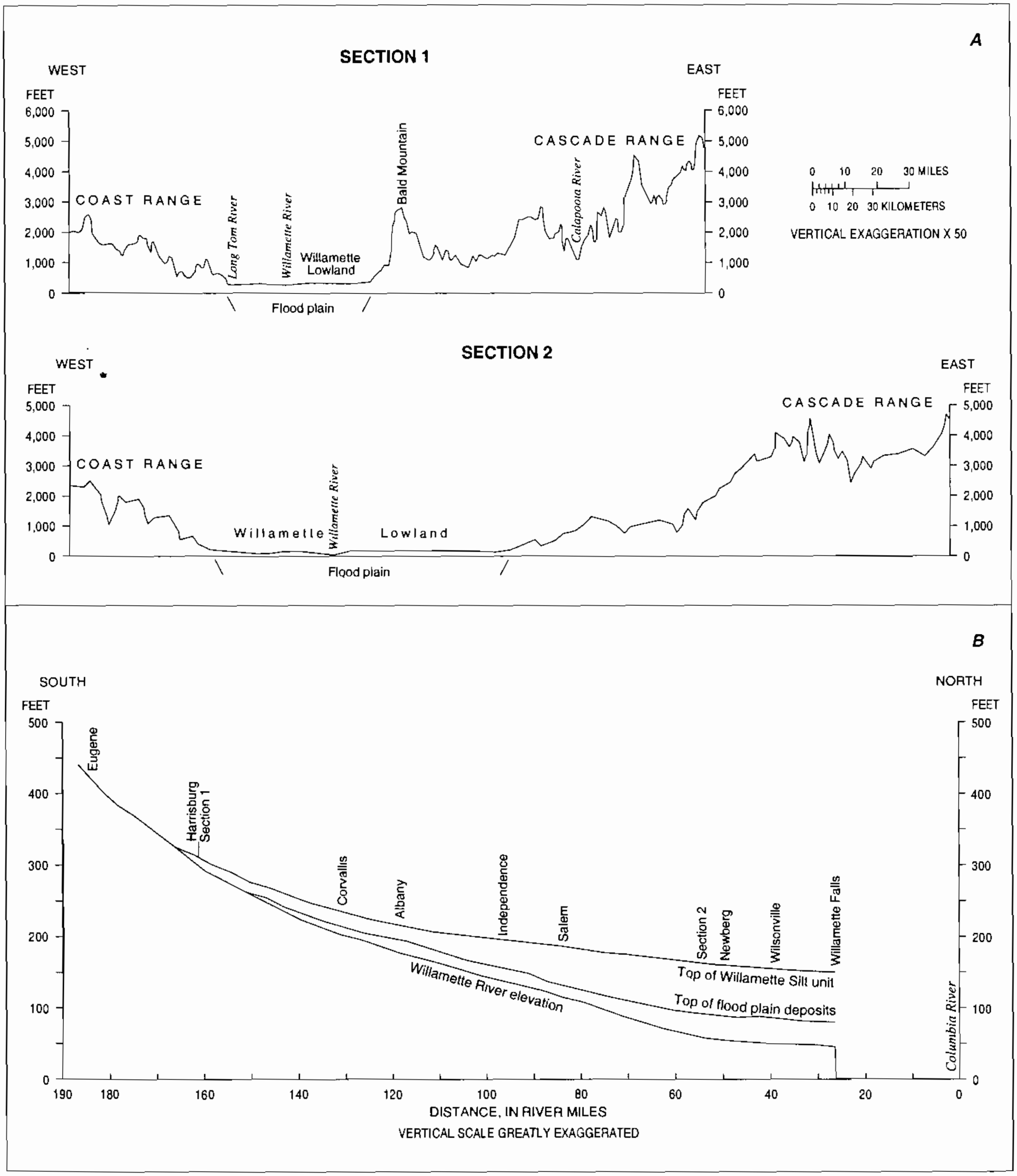

FIGURE 3. (A) Topographic sections west-east across study area and (B) Bank section along Willamette River. (Trace of topographic sections shown on figure 2.)

The permeability of the subsoil and of the substrata ranges from moderately low (0.2 to 0.8 in/hr [inches per hour]) to high (5 to 10 in/hr), and the total available water-holding capacity generally is high (greater than 10 inches), although some soils have a medium value (6 to 10 inches). Soils overlying the buried alluvial fans generally are gravelly loams to gravelly silt or clay loams. Soil depth is typically 15 to 40 inches over gravel; the permeability is moderate (0.8 to 2.5 in/hr) to very high (greater than 10 in/hr), and the total available water-holding capacity is low (less than 6 inches). Soils in the rest of the lowland are silty clay loams more than 5 ft thick and have moderately slow permeability (0.2 to 0.8 in/hr). Total available water-holding capacity is high (greater than 10 inches). The soils of the Willamette River drainage have an estimated water-holding capacity of at least 4.27 million acre-ft (acre-feet), an average of 6.74 inches over the entire watershed (Pacific Northwest River Basins Commission, 1971a).

GENERAL HYDROLOGY

The relation among the three water phases of the hydrologic cycle—atmospheric water, surface water, and subsurface water—is evident in the Willamette Lowland. For example, the October through March rainy season (accounting for 80 percent of the mean annual precipitation) initiates the November through April high-flow period for streams (accounting for from 70 to 90 percent of the mean annual discharge). Coincident seasonal peaks in atmospheric and surface water are different from the delayed peak in subsurface water storage; a regional high in the water table generally occurs during December through March. Aspects of the climate (including atmospheric water) and surface water in the Willamette Lowland are described in this section.

CLIMATE

The Willamette Lowland is in the rain shadow of the Coast Range, and its climate is characterized by wet, mild winters and dry, warm summers. Most of the precipitation is caused by the movement of low-pressure weather systems along a fairly well-defined path from the north Pacific Ocean eastward over the continent. Because the usual summer and early fall path of these storm systems is well north of the area, precipitation is slight during this period (only about 6 percent of the annual precipitation falls in the summer). The rainy season begins in the fall, usually in late September or early October, when the storm path shifts southward, and continues until March or April. Mean monthly precipitation data from selected weather stations in the study area indicate that about 80 percent of the mean annual precipitation falls from October through March (fig. 4).

Mean annual precipitation in the Willamette Lowland ranges from about 37 inches near Portland, Oregon, to more than 80 inches along parts of the western and eastern boundaries of the study area (fig. 4). Mean annual precipitation of the entire study area is about 51 inches and is 46.1 inches in the lowland area. At altitudes under 500 ft, most of the precipitation occurs as rain; the part of the annual precipitation that falls as snow increases about 10 percent for each 1,000-ft increase in altitude.

Mean annual maximum air temperatures range from about 60°F (degrees Fahrenheit) 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, summer temperatures in the lowlands range from 60 to 90°F and winter temperatures range from 30 to 50°F. The growing season is more than 200 days at lower altitudes and is about 150 days in the higher valleys and foothills.

SURFACE-WATER RESOURCES

The Columbia River, which crosses the northern part of the study area and separates Oregon and Washington, is the major river in the region. The Columbia River discharges to the Pacific Ocean, about 100 mi northwest of the mouth of the Willamette River.

The Willamette River, the major river in the study area, begins at the junction of the Coast Fork and Middle Fork Willamette Rivers near Eugene, Oregon, and flows northward through the Willamette Valley to its confluence with the Columbia River near Portland, Oregon—a distance of 187 mi. The Willamette River is from 200 to 1,000 ft wide, averaging about 500 ft wide. The gradient of the river from the confluence of the Coast and Middle Forks to its mouth averages 2.2 ft/mi (feet per mile) and ranges from about 5 ft/mi between Eugene and Harrisburg, Oregon, to about 0.04 ft/mi between Newberg and the Willamette Falls at Oregon City, Oregon (fig. 3b); backwater from the 40-ft high Willamette Falls is largely responsible for the low gradient in the Newberg-Oregon City reach. The falls are created by an outcrop of relatively erosion-resistant rocks of the Columbia River Basalt Group; the pool above the falls begins at about 50 ft above sea level. Water levels in the Willamette River below the falls are affected by tides in the Pacific Ocean and fluctuate as much as 2 ft during a tidal cycle (Glenn, 1965).

Almost all of the Willamette River's discharge is derived from 15 major tributaries (fig. 5). The mean annual discharge of the Willamette River at Portland, Oregon, is 32,180 ft^3/s (cubic feet per second) (table 1), an average of about 40 in/yr (inches per year) from the 11,100-mi^2 drainage area.; however, the timing and quantity of the discharge do not represent natural runoff because (1) streamflow is regulated by many reservoirs, and (2) many municipal and agricultural irrigation systems divert water.

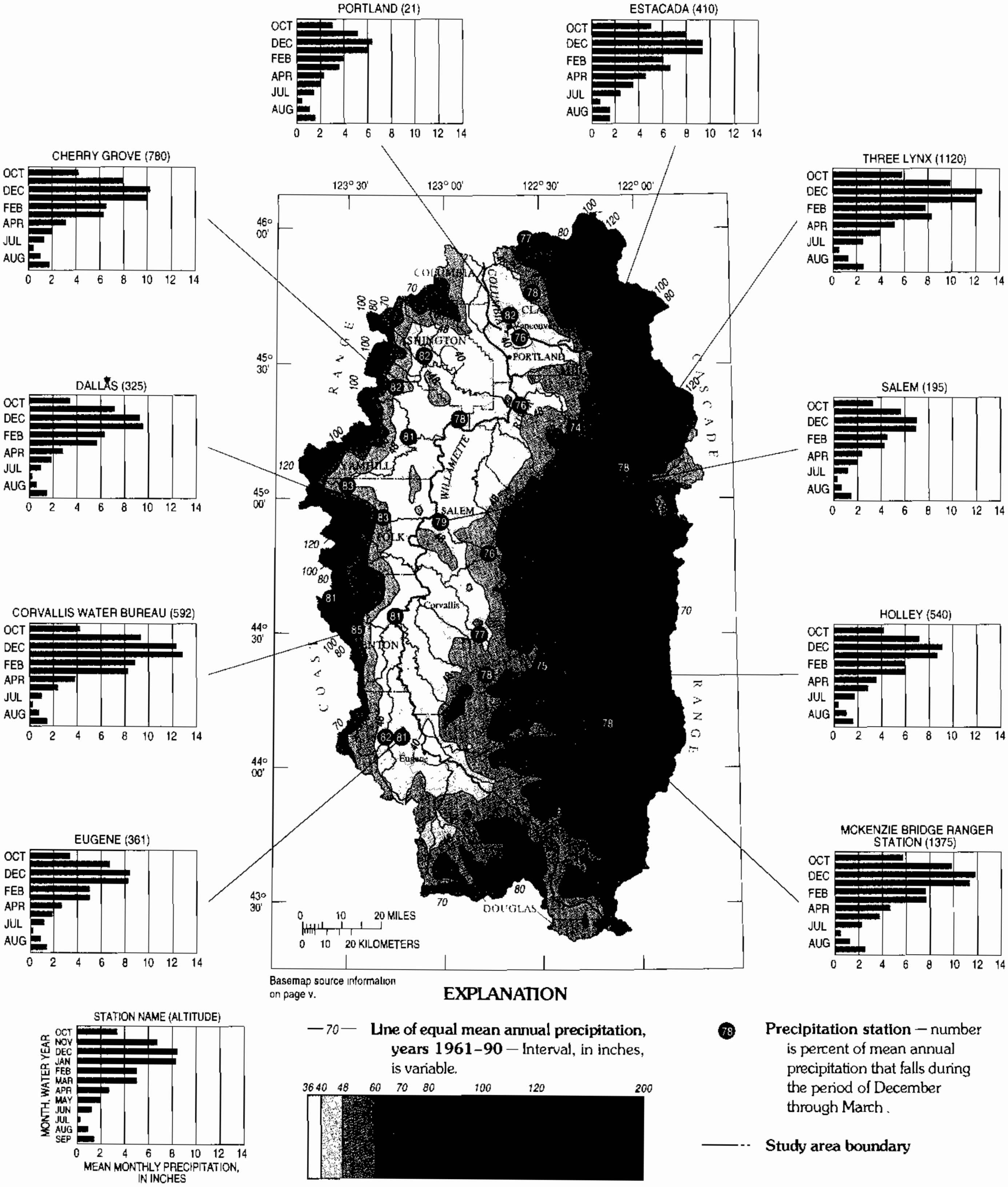

FIGURE 4.—Mean annual and mean monthly precipitation for the study area. (Precipitation data from Taylor, 1993.)

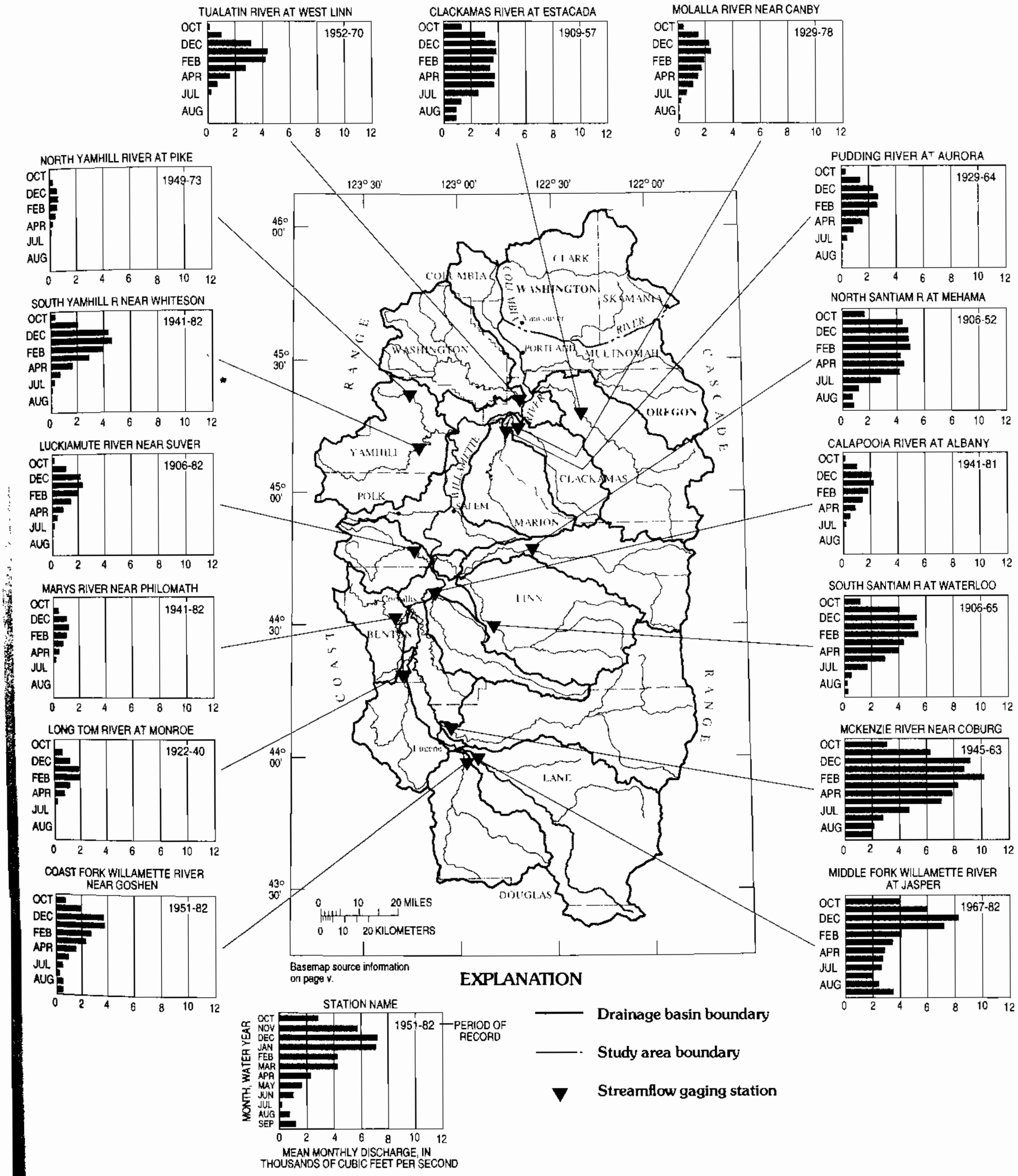

FIGURE 5.—Mean monthly discharge for selected major tributaries of the Willamette River.

TABLE 1.—*Discharge characteristics for selected rivers, Willamette Lowland, Oregon and Washington*

[mi2, square miles; ft3/s, cubic feet per second; --, not regulated]

Name of gaging station[1]	Drainage area (mi2)	Year flow regulation began	Annual discharge (ft^3/s) of Minimum	Mean	Maximum	Period record
Middle Fork Willamette River at Jasper	1,340	1953	1,880	4,060	6,220	1967–91
Coast Fork Willamette River near Goshen	642	1942	510	1,600	2,700	1951–91
McKenzie River near Coburg	1,337	1963	4,580	6,020	8,280	1945–63
Long Tom River at Monroe	391	1941	310	700	1,230	1922–40
Marys River near Philomath	159	--	100	460	820	1941–82
Calapooia River at Albany	372	--	240	900	1,510	1941–81
South Santiam River at Waterloo	640	1966	1,700	2,910	4,550	1906–65
North Santiam River at Mehama	655	1953	2,060	3,250	4,330	1906–52
Santiam River at Jefferson	1,790	1953	4,250	7,600	11,630	1908–53
Luckiamute River near Suver	240	--	230	890	1,460	1905–91
South Yamhill River near Whiteson	502	--	460	1,720	3,120	1940–91
North Yamhill River at Pike	67	--	160	240	370	1949–73
Molalla River near Canby	323	--	520	1,160	1,820	1929–78
Pudding River at Aurora	479	--	700	1,220	1,980	1929–64
Tualatin River at West Linn	706	1975	1,050	1,530	2,540	1952–70
Clackamas River at Estacada	671	1958	1,660	2,690	3,920	1909–57
Clackamas River near Clackamas	930	1958	1,720	3,640	5,720	1963–82
Willamette River at Portland	11,100	1941	13,710	32,180	54,490	1973–91
East Fork Lewis River near Heisson	125	--	417	757	1,117	1930–79

[1] All rivers located in Oregon except the East Fork Lewis River.

The stream discharge is derived principally from rainfall runoff. Additionally, snowmelt from some of the eastern tributaries provides increased flows into the late spring, and ground-water discharge contributes to streamflow as well (particularly to most stream reaches in the lowland areas). The discharge pattern coincides with the precipitation pattern. Although the total amount of runoff is very different between wet and dry years (Oster, 1968), the seasonal pattern of runoff in both wet and dry years is similar. Generally, the initial rains of the early fall recharge the soil zone and contribute little runoff. After the soil has reached field capacity, runoff begins to increase. By November, runoff closely corresponds to the pattern of precipitation, and the largest monthly flows occur throughout the study area between November and April (fig. 5)—a direct result of heavy rains and some early snowmelt. The combination of warm winter temperatures and heavy rains falling on snow generally results in the largest rates and volumes of runoff, as exemplified by the disastrous floods of December 1964 and February 1996. Runoff also is large during the spring, when streams draining the Cascade Range carry large volumes of snowmelt. Throughout the study area, streams recede to minimum flows between July and October, when precipitation is lowest and the temperature is relatively high.

There are marked differences in the volume and seasonal distribution of tributary discharge (Friday and Miller, 1984). The differences are a function of which mountain range a stream drains. The major eastern tributaries (Clackamas, Molalla, Pudding, North Santiam, South Santiam, Calapooia, McKenzie, and Middle Fork Willamette Rivers) drain about 60 percent of the Willamette River Basin and account for about 75 percent of the mean annual discharge of the Willamette River Basin (table 1, using data from the Santiam River at Jefferson gage to represent the combined influence of the North Santiam and South Santiam Rivers). These eastern tributaries contribute more (and seasonally prolonged) discharge compared with the western tributaries because they have drainage basins that (1) are larger, (2) are at higher altitudes, (3) receive more rainfall, (4) receive more snow, (5) are capable of receiving and transmitting more ground water, and (6) contain permanent glaciers.

The major western tributaries (Tualatin, North Yamhill, South Yamhill, Luckiamute, Marys, and Long Tom Rivers) drain the Coast Range and its foothills and account for about 17 percent of the mean annual discharge of the Willamette River Basin (table 1). The Coast Range was not subject to glaciation and, as a result, does not contain large glacially derived alluvial valleys that store and transmit large quantities of ground water.

Because the drainage basins of the western tributaries do not head in high terrain, snowmelt does not provide substantial discharge, and the basins are smaller than those in the Cascade Range.

The Coast Fork Willamette River drains the upland south of the Willamette Valley, where the Coast and Cascade Ranges merge, and accounts for about 5 percent of the mean annual discharge of the Willamette River Basin. The Lewis River drains the upland north of the Willamette Lowland in Clark County, Washington, and coincides with the northern boundary of the study area (fig. 1).

The discharge characteristics of the major tributaries to the Willamette River illustrate some of these differences and also some unique trends (fig. 5).

1. The major drainage basins on the west that extend to the crest of the Coast Range, and to the Pudding River and Calapooia River Basins, which are located at lower altitudes in the central and eastern parts of the valley, transmit about 90 percent of their annual discharge during the November through April wet season.
2. The major drainage basins on the east that extend only part way up the Cascade Range (Molalla River and South Santiam River Basins) transmit about 80 percent of their annual discharge during the November through April wet season.
3. The major drainage basins on the east that extend to the crest of the Cascade Range and contain glaciers transmit about 70 percent of their annual discharge during the November through April wet season.
4. The discharges to the Coast Fork and Middle Fork Willamette Rivers have been regulated by upstream reservoirs. The Coast Fork transmits about 80 percent of its annual discharge during the November through April wet season; the Middle Fork, which is more regulated, transmits about 65 percent during the wet season.

The differences in magnitude between Coast Range derived discharge and Cascade Range derived discharge are even greater during low-flow periods. The mean August discharge of the seven major eastern tributaries below the confluence of the Coast and Middle Forks of the Willamette River is about 25 times larger than that of the six western tributaries (fig. 5). A large quantity of winter and spring runoff that infiltrates the porous lava along the crest of the Cascade Range is transmitted to lower elevations, where it discharges through springs and seeps; these ground-water releases provide a large part of the summer flows of streams originating in the Cascade Range (Pacific Northwest River Basins Commission, 1971c). The mean August discharge of the McKenzie River (2,150 ft^3/s) is about 48 percent of the mean August discharge of all the tributaries combined (4,510 ft^3/s); much of the sustained discharge by the McKenzie River during the low-flow period probably is derived from meltwater from the glaciers in the drainage basin.

Major basinwide floods in the Willamette Valley generally occur from November through February, but floods may occur from October through April. Most of these floods result from intense rainfall, usually augmented by melting snow. In the headwaters, runoff follows rainfall by a few hours, whereas floods crest on the lower Willamette River about 3 days after the period of maximum precipitation (Pacific Northwest River Basins Commission, 1971a).

At present (1998), there are 17 major reservoirs in the Willamette River Basin and 3 reservoirs in Clark County, Washington (table 2). The storage in these reservoirs has been allocated for flood control, power, irrigation, improvement of navigation, conservation, pollution abatement, water supply, and recreation. These multiple-purpose reservoirs provide a combined total capacity of 3,382,400 acre-ft for flood control and a combined usable capacity of 2,502,300 acre-ft (table 2).

PREVIOUS HYDROGEOLOGIC INVESTIGATIONS

Previous studies of ground-water resources (fig. 6) in the Willamette Lowland area have occurred in four phases. A list of most of these studies, plus many additional studies, was compiled as part of this study (Morgan and Weatherby, 1992). Piper (1942) began the initial phase in 1928, not only with the first ground-water appraisal, but also with the only previous study that encompassed most of the Willamette Valley. Piper's work established a foundation for describing and delineating the hydrogeologic regime in the lowland; he produced the first regional geologic and ground-water-level maps of the area, conducted an extensive well inventory, established a water-level observation network, and characterized regional water-quality characteristics for various types of deposits. Griffin and others (1956) completed an assessment of the water resources in the Portland Basin; this assessment established the framework for later studies.

The second phase extended from the mid-1960's to the mid-1970's and involved smaller areal ground-water appraisals of parts of the lowland. These areal studies began in the northern part of the lowland and moved progressively south. In the Portland Basin, Mundorff (1964) prepared a detailed analysis of the geology and a description of a major alluvial aquifer along the Columbia River in Clark County, Washington. Additionally, his report included a surface-water availability appraisal and a description of water quality in the major aquifer.

TABLE 2.—*Major reservoirs and storage capacity in the Willamette Lowland, Oregon and Washington*

[mi2, square miles; F, flood control; P, power; R, recreation; N, navigation; I, irrigation; Pn, pollution; C, conservation]

Name	Drainage area (mi^2)	Capacity (acre-feet) Usable	Capacity (acre-feet) Total	Use	In-service year for storage
		Willamette Lowland (Oregon)			
Big Cliff Reservoir	449	2,900	6,500	F,P,R	1953
Blue River Lake	87	85,600	89,500	F	1968
Cottage Grove Lake	104	33,000	33,000	F,N	1942
Cougar Lake	207	164,800	219,100	F,P	1963
Detroit Lake	437	340,000	455,100	F,P,I,N,Pn	1953
Dexter Lake	5	27,500	27,500	P,R	1955
Dorena Lake	265	77,600	77,600	F,N	1949
Fall Creek Lake	184	115,500	125,000	F,R,C	1965
Fern Ridge Lake	273	101,100	116,800	F,N	1941
Foster Lake	492	33,200	60,800	F,P,Pn	1966
Green Peter Lake	273	330,800	428,100	F,P,N,Pn	1966
Henry Hagg Lake	39	56,200	63,400	F,R,I	1975
Hills Creek Lake	389	248,900	356,000	F,P	1961
Lookout Point Lake	991	349,200	456,000	F,P,N,Pn	1953
North Fork Reservoir	658	19,000	19,000	F,P,R	1958
Smith River Reservoir	18	9,900	15,000	P	1963
Timothy Lake	54	64,500	65,700	P	1956
Total		2,059,700	2,548,400		
		Willamette Lowland (Washington)			
Lacamas Lake	64	7,500	7,500	R	1936
Lake Merwin	730	245,600	424,000	P	1931
Yale Reservoir	596	189,500	402,500	P	1952
Total		442,600	834,000		

Brown (1963) conducted an appraisal of the ground-water resources in the west-side business district of Portland, Oregon, where extensive ground-water withdrawals were used for industrial purposes. Hogenson and Foxworthy (1965) studied the ground water in the east Portland area and discussed its water-quality characteristics; the authors concluded that the principal water-bearing rocks were sandstone, fluviolacustrine deposits, and alluvial deposits. A report on the geology and ground-water resources in the Tualatin Basin by Hart and Newcomb (1965) showed that ground water occurs principally in basalt of the Columbia River Basalt Group and that the water generally is of good quality.

Areal ground-water appraisals in the central Willamette Valley began with Price (1967a), who reported on the geology and ground-water conditions in the French Prairie area. The principal ground-water reservoir was determined to consist of nonmarine sedimentary deposits that yielded large volumes of water to wells. Price (1967b) also found that sandstone and alluvial deposits were the most productive units in the Eola-Amity Hills area and that the underlying Columbia River Basalt Group rocks yielded smaller quantities. Most of the ground water in this area was found to be suitable for irrigation and other uses; ground water at depth, however, commonly contained large concentrations of chloride (Price, 1967b). Hampton (1972) described the geology and ground-water resources of the Molalla-Salem Slope area; this work included a description of the quality of the ground water. Foxworthy (1970) studied the aquifers in the Columbia River Basalt Group rocks in the Salem Heights area. Frank and Collins (1978), in their study of the ground water in the Newberg area, determined that the Columbia River Basalt Group was the principal ground-water source in that area.

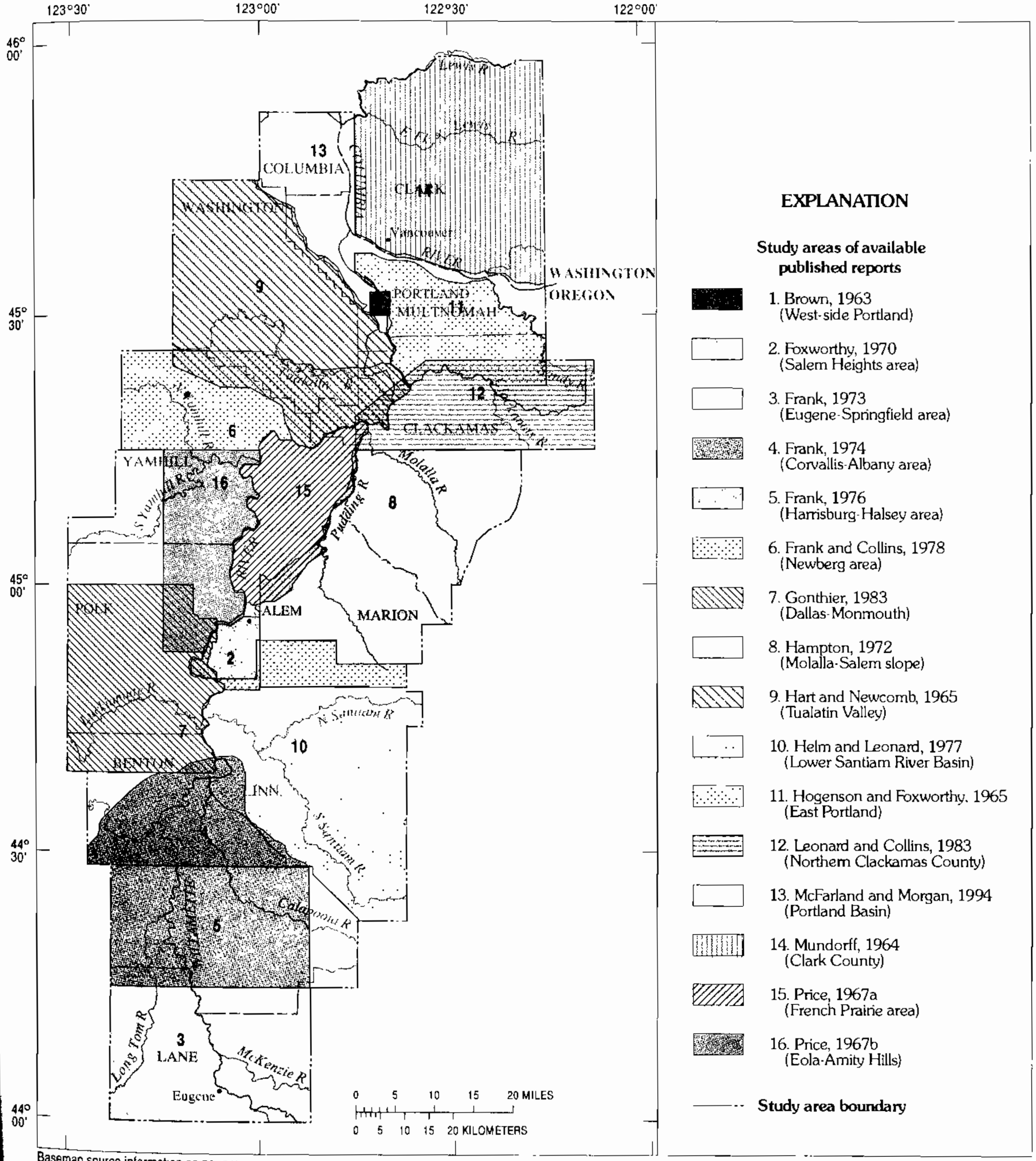

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FIGURE 6.—Study areas of U.S. Geological Survey Water-Supply Papers and State of Oregon Ground Water Reports in the Willamette Lowland.

Areal ground-water studies in the southern Willamette Valley include work by Helm and Leonard (1977), who studied the lower Santiam River Basin area. Frank (1974) found ground water in the Corvallis-Albany area to be suitable for domestic use if obtained from shallow unconsolidated deposits, which were the most productive rock units in the area. Locally, in the Corvallis area, water from older marine sedimentary rocks was too saline for most uses. In the Harrisburg-Halsey area, alluvial deposits were the principal water source for wells, and underlying rocks yielded only small quantities of water (Frank, 1976); much of the deeper ground water had large concentrations of dissolved solids and was too saline for most uses. Frank (1973) reported that unconsolidated deposits were the most productive aquifers in the Eugene-Springfield area and that water levels in the alluvial deposits were closely related to stream-stage fluctuations of the McKenzie and Willamette Rivers.

The third phase covered the early 1980's, when studies of the two remaining major areas within the lowland were completed. Leonard and Collins (1983) completed a ground-water study of northern Clackamas County, and Gonthier (1983) studied the Dallas-Monmouth area. McFarland (1983) described the lithology and water-bearing characteristics of seven major groups of rock units in western Oregon; the most extensive water-yielding units identified were the unconsolidated deposits (basin fill and Recent alluvium) in the Willamette Lowland.

The fourth phase began in the late 1980's and involved a detailed analysis of the ground-water resources in the Portland Basin. Swanson and others (1993) presented a detailed description of the geologic framework, McFarland and Morgan (1996) described the flow system, Morgan and McFarland (1996) provided a numerical simulation of the ground-water flow system, Snyder and others (1994) quantified the ground-water recharge, Collins and Broad (1993) quantified the ground-water pumpage in the area for 1987–88, and Turney (1990) described the quality of ground water in Clark County, Washington.

HYDROGEOLOGIC FRAMEWORK OF AQUIFER SYSTEM

The Willamette Lowland is composed of four structural basins separated by folded and faulted outcrops of the Columbia River Basalt Group. The Willamette Lowland aquifer system in each basin, although hydraulically connected through a series of restrictive water gaps (geologic constrictions), is distinctive. The aquifer system consists of two regional aquifers, the Willamette aquifer and the Columbia River basalt aquifer, which are generally separated by a thick, silty clay—the Willamette confining unit. However, in a few areas, the confining unit is absent, and the two aquifers are in direct hydraulic connection. The primary aquifer, which is generally composed of unconsolidated deposits in the Willamette Lowland, occurs in three of the four basins—the Portland Basin, the central Willamette Valley, and the southern Willamette Valley. Another aquifer, which is composed of the Columbia River Basalt Group, occurs primarily in three of the structural basins—the Portland Basin, the Tualatin Basin, and the central Willamette Valley.

FRAMEWORK OF REGIONAL AQUIFER SYSTEM

The Willamette Lowland is a structural and erosional lowland situated between uplifted marine rocks of the Coast Range and volcanic rocks of the Cascade Range. The Coast Range consists of Tertiary marine sandstone, siltstone, shale, and associated volcanic and intrusive rocks of predominantly basaltic composition. The Cascade Range consists of a variety of lava flows, ash-flow tuffs, and pyroclastic and epiclastic volcanic debris. Cascade Range rocks and marine strata interfinger beneath and adjacent to the Willamette Lowland.

In the northern two-thirds of the Willamette Lowland, the marine sedimentary rocks and Cascade Range volcanic rocks are overlain by as much as 1,000 ft of the middle Miocene Columbia River Basalt Group lava that flowed into the region early during the development of the lowland. Folding and faulting during and after the incursion of this lava formed the four major depositional basins (fig. 2). These basins, separated in most places by uplands composed of the Columbia River Basalt Group, have locally accumulated more than 1,600 ft of fluvial sediment, primarily derived from the Cascade and Coast Ranges. These basin-fill sediments cover about 3,100 mi^2 of the lowland.

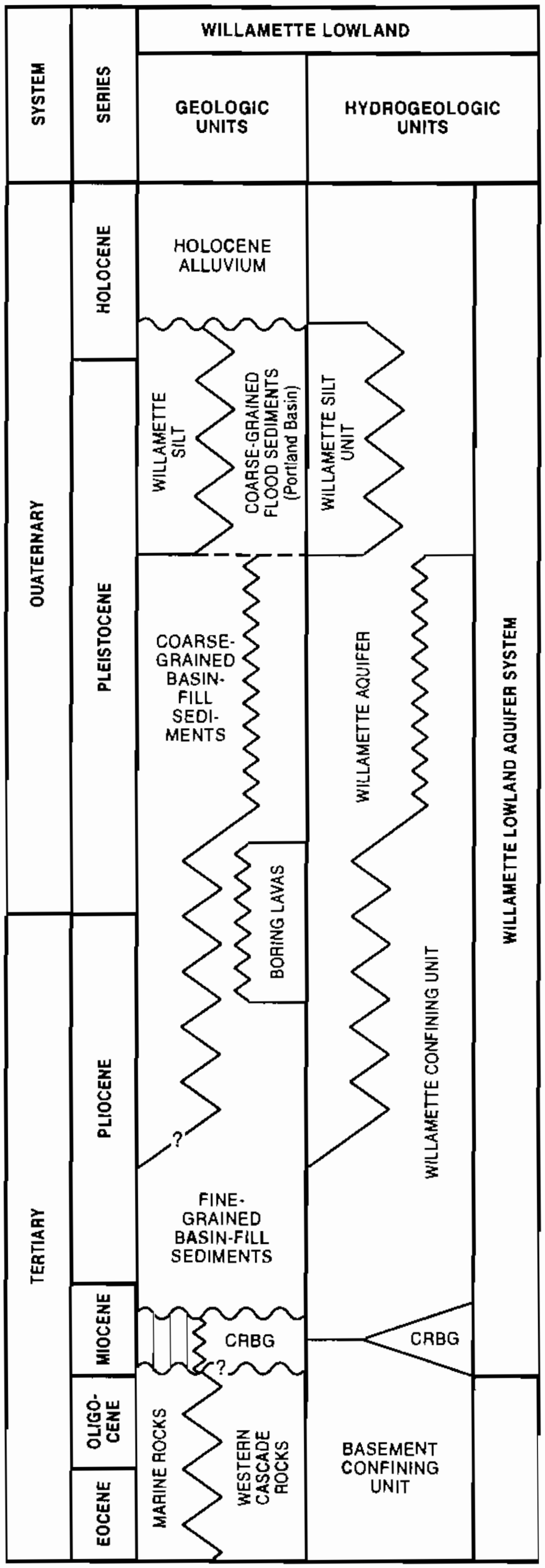
During Pleistocene time, large-volume glacial-outburst floods, originating in western Montana, flowed down the Columbia River drainage and periodically inundated the Willamette Lowland. These floods deposited as much as 250 ft of silt, sand, and gravel in the Portland Basin and as much as 130 ft of silt elsewhere in the Willamette Lowland.

REGIONAL HYDROGEOLOGIC UNITS

Five regional hydrogeologic units, each consisting of one or more recognized geologic units, have been defined for this study (Gannett and Caldwell, 1998). Geologic units that have similar overall hydrogeologic characteristics and are adjacent or occupy similar stratigraphic positions were combined into a single hydrogeologic unit. The five hydrogeologic units, from oldest to youngest, are (1) the basement confining unit, (2) the Columbia River basalt aquifer, (3) the Willamette confining unit, (4) the Willamette aquifer, and (5) the Willamette Silt unit. These units each have relatively uniform and distinct hydrologic properties. A correlation chart showing the relation between hydrogeologic and geologic units is presented in figure 7. A map of the surficial extent of the regional hydrogeologic units (fig. 8) and the two hydrogeologic sections (fig. 9) show the three-dimensional framework of the aquifer system.

In their work in the Portland Basin, Swanson and others (1993) included the Boring Lava in the Troutdale gravel aquifer (considered to be part of the Willamette aquifer in this regional study). Where the Boring Lava is most extensive in the study area—on the plateau between the Portland Basin and the central Willamette Valley—it overlies fine-grained sediment of the Willamette confining unit and is hydraulically distinct from the Willamette aquifer. Because a number of wells yield water from the Boring Lava, the formation is shown on figure 8; however, the formation is limited in extent and is not considered a regional hydrogeologic unit for this study.

The basement confining unit forms the lateral and basal boundary to the Willamette Lowland aquifer system. The basement confining unit includes all the stratigraphic units that underlie either the Columbia River Basalt Group in the northern part of the lowland or the basin-fill deposits in the southern part (fig. 9). The unit is composed of Tertiary marine sedimentary rocks and Eocene volcanic rocks of the Coast Range and volcanic rocks of the western Cascade Range. Tertiary marine sandstone, siltstone, claystone, and shale are exposed in the Coast Range and underlie most of the southern and central Willamette Valley, the entire Tualatin Basin, and the western part of the Portland Basin. Marine sedimentary rocks and western Cascade volcanic rocks are exposed in the Cascade Range foothills and underlie the eastern parts of the southern and the central Willamette Valley and the eastern part of the Portland Basin (fig. 8). The contact relation between marine strata and Cascade Range volcanic rocks beneath the Willamette Lowland is poorly known.



NOTE: CRBG = COLUMBIA RIVER BASALT GROUP

FIGURE 7.—Regional relation between generalized geologic units and hydrogeologic units in the Willamette Lowland.

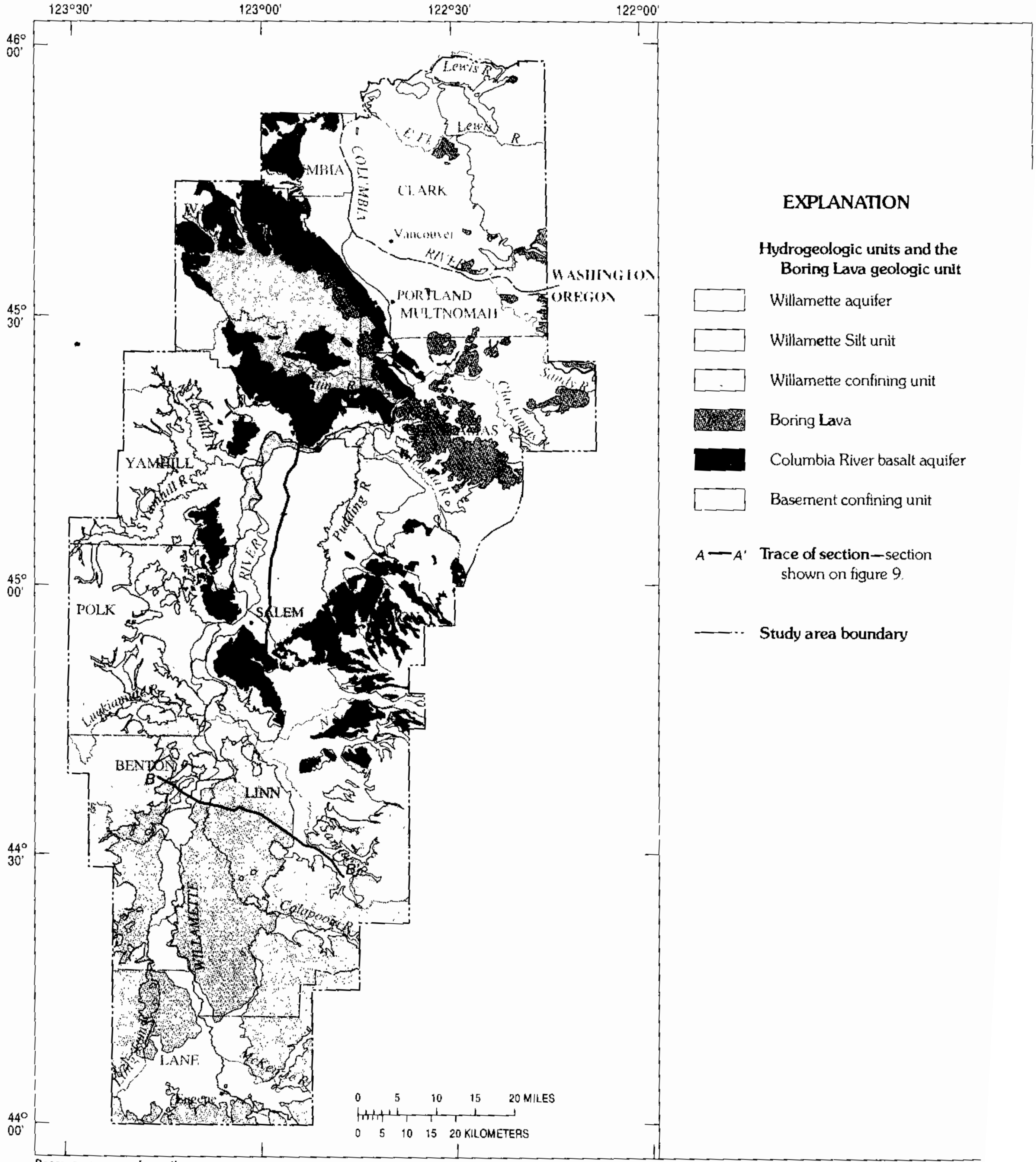


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FIGURE 8.—Surficial extent of hydrogeologic units and the Boring Lava.

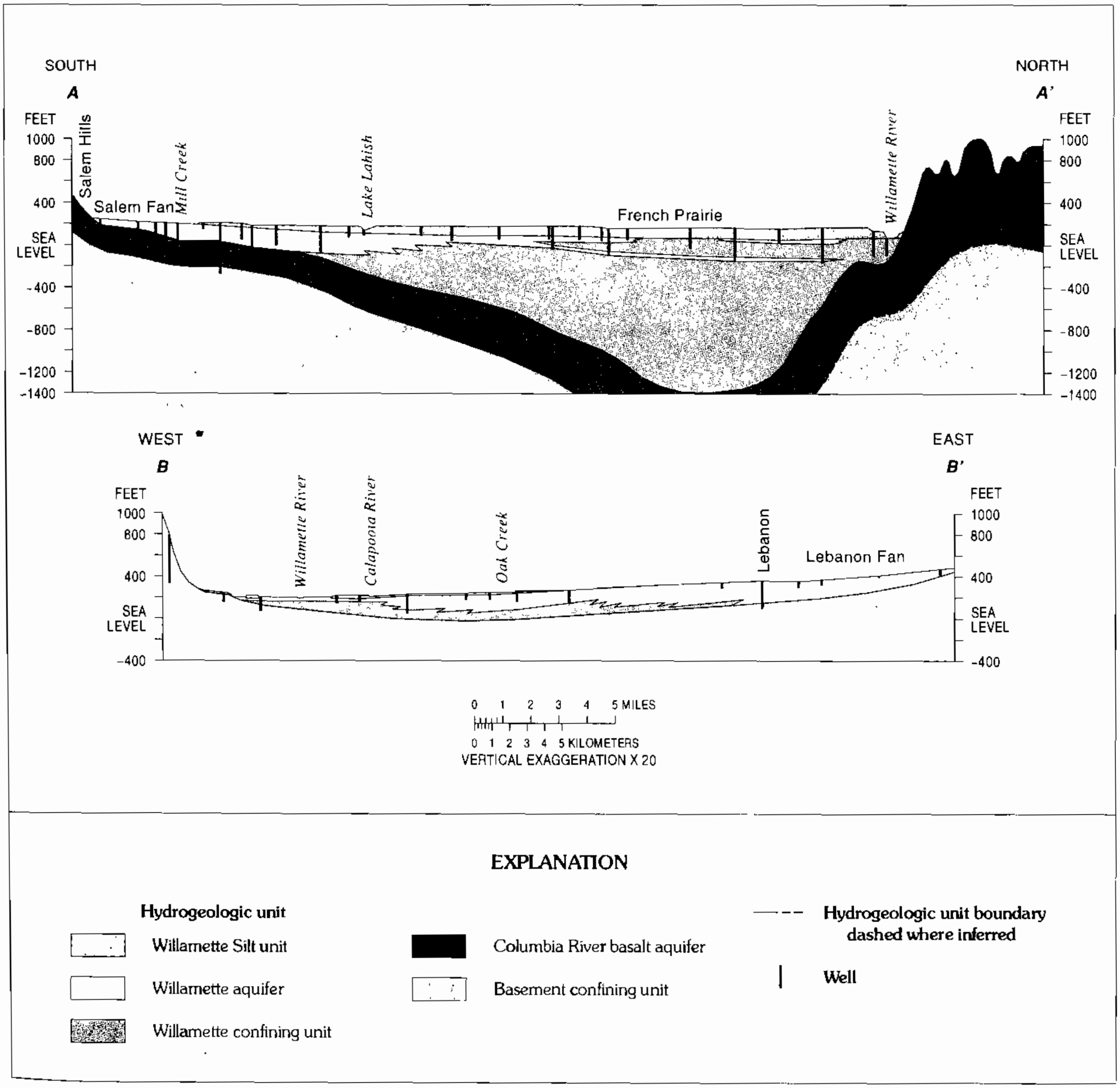

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FIGURE 9.—Hydrogeologic sections. (*A–A'*–North-south section in central Willamette Valley. *B–B'*–East-west section in southern Willamette Valley. Trace of sections shown on figure 8.)

The Columbia River basalt aquifer overlies the basement confining unit over 2,500 mi^2 of the northern part of the Willamette Lowland (fig. 10) and consists of layers of basalt flows of the Columbia River Basalt Group. The thickness of the aquifer generally is several hundred feet but locally is as much as 1,000 ft. The top of the Columbia River basalt aquifer was mapped (Gannett and Caldwell, 1998) by using information from water well logs, oil and gas exploration well logs, and seismic reflection interpretations from Werner (1990) and Yeats and others (1991). The top of the Columbia River basalt aquifer coincides with the structure contours of the base of the Willamette confining unit in the northern part of the lowland (fig. 11).

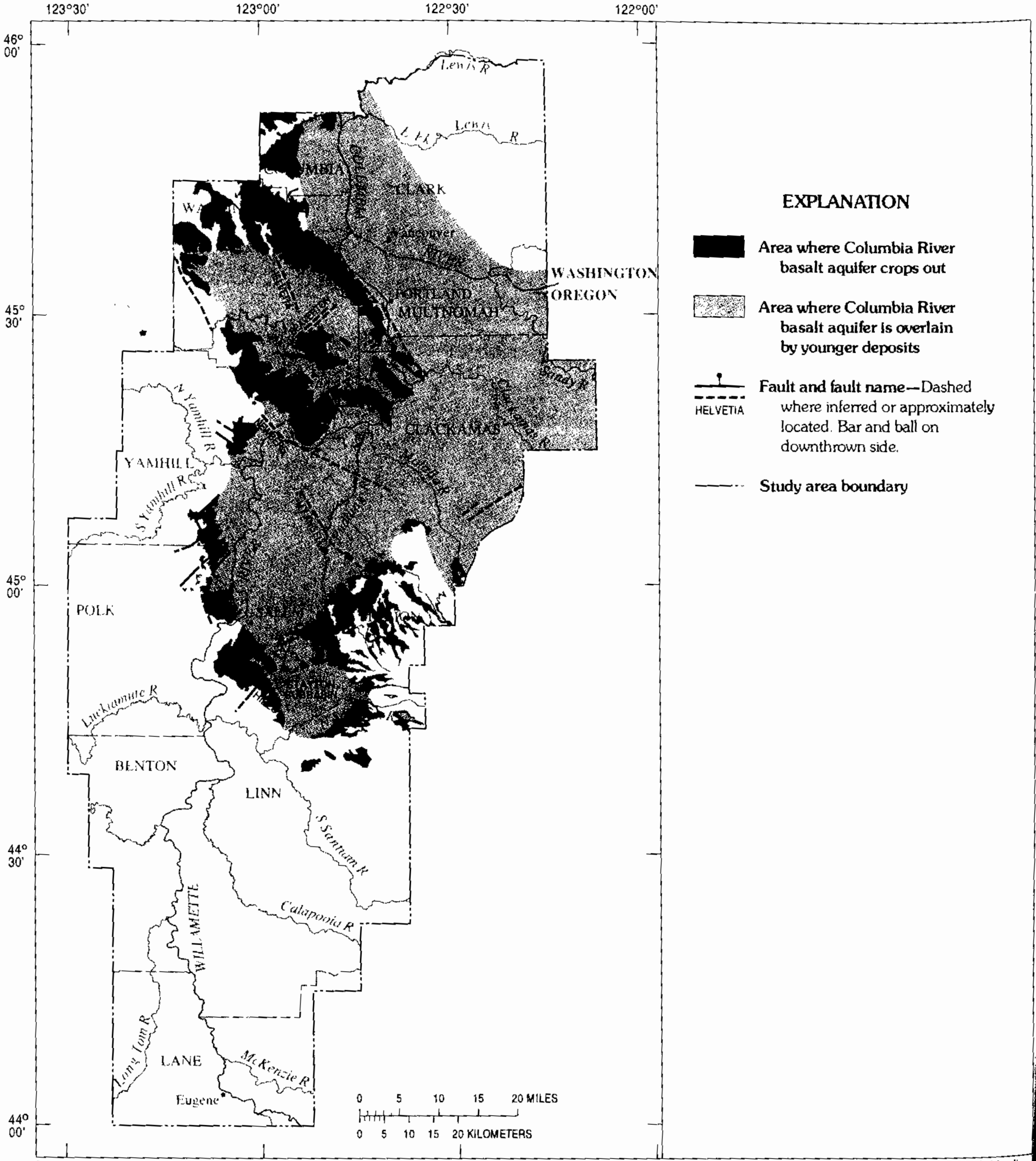

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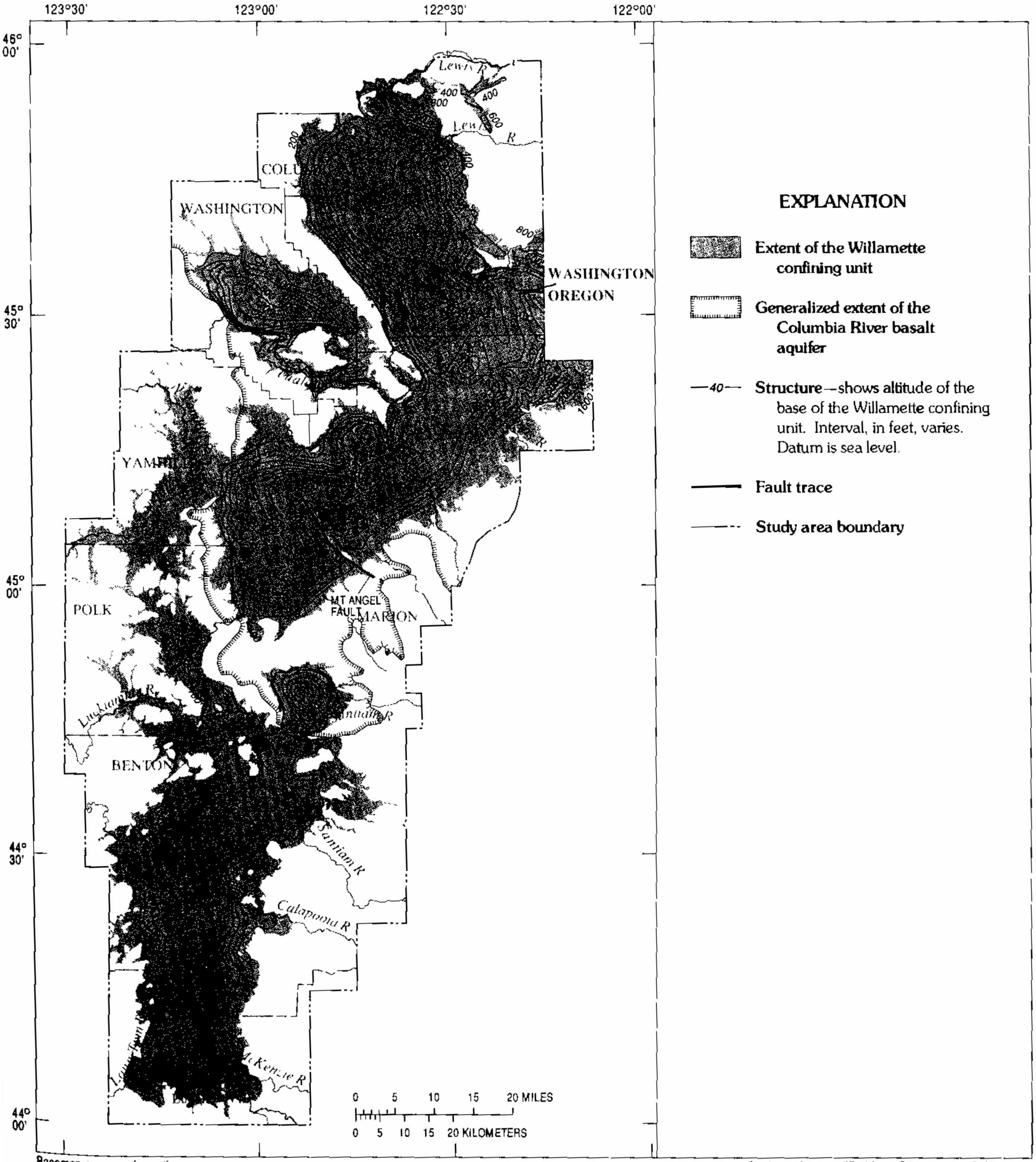
FIGURE 10.—Extent of the Columbia River basalt aquifer.



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Geologic data modified from Gannett and Caldwell, 1998, USGS Professional Paper 1424–A

FIGURE 11.—Altitude of the base of the Willamette confining unit.

The Columbia River basalt aquifer is overlain by basin-fill deposits over about 1,900 mi^2 and crops out over an area of about 600 mi^2 (fig. 10) in the uplands that separate the southern and central Willamette Valley, the Portland Basin, and the Tualatin Basin.

The Willamette confining unit underlies about 3,100 mi^2 of the aquifer system (fig. 11) and crops out over an area of about 225 mi^2. The unit consists primarily of fine-grained, distal alluvial fan and low-gradient stream deposits. The fine-grained deposits are considered a regional confining unit because of their widespread occurrence and low permeability; the sediment of the Willamette confining unit is commonly described by drillers as blue clay, sandy clay, or shale. The fine-grained deposits occur in the lower part of the basin-fill sequence and dominate the sequence in areas distant from major alluvial fans. The thickness of the Willamette confining unit ranges from 0 to more than 1,600 ft and is more than 1,400 ft thick in the central parts of the Portland and Tualatin Basins and the central Willamette Valley (fig. 12). In the Tualatin Basin, the upper part of the Willamette confining unit is composed of the Willamette Silt because the intervening Willamette aquifer is absent. Volumetrically, the Willamette confining unit is the largest unit in the aquifer system. The unit overlies the Columbia River basalt aquifer in the northern part of the lowland, and it overlies the basement confining unit in the southern part.

The Willamette aquifer is the principal aquifer unit in the Willamette Lowland. The unit extends about 2,700 mi^2 and ranges in thickness from less than 20 to more than 400 ft, locally exceeding 600 ft (fig. 13). The Willamette aquifer crops out over an area of about 1,640 mi^2 and primarily consists of coarse-grained proximal alluvial-fan and braided-stream deposits. These deposits generally occur in the upper part of the basin-fill sequence and dominate the sequence in areas where major drainages debouch into the Willamette Lowland.

These coarse-grained deposits are composed primarily of layers of sand and gravel that are a few tens to several tens of feet thick; interbeds of sand, silt, and clay commonly occur but, generally, are thinner and fewer in number than their coarse-grained counterparts. The sand and gravel layers exhibit a wide range of sorting and cementation. Many layers are described as mixtures of clay, sand, and gravel. In the Portland Basin, the Willamette aquifer consists of as much as 600 ft of silt, sand, and gravel.

The greatest thicknesses and coarsest materials of the Willamette aquifer outside of the Portland Basin occur in six major alluvial fans (fig. 13) that were deposited where major streams from the Cascade Range enter the Willamette Lowland. Gravel and sand in the deeper part of the alluvial fans grade laterally into, and interfinger with, fine-grained sediment of the Willamette confining unit (fig. 9). The boundary between the coarse sediment of the Willamette aquifer and fine sediment of the Willamette confining unit is commonly the facies boundary between the coarse-grained proximal and fine-grained distal alluvial-fan facies.

A thinner, but more laterally extensive, layer of gravel occurs near the top of the Willamette aquifer. This gravel, which averages 20 to 40 ft thick, corresponds in part to the Linn gravel of Allison (1953) and the Rowland Formation of Balster and Parsons (1969). It occurs over much of the southern Willamette Valley and eastern parts of the central Willamette Valley. This widespread gravel probably was deposited during Pleistocene time, when large volumes of glacial sediment were delivered to the alluvial fans and caused coarse sediment deposition to extend out from the fans onto the valley floor.

The Willamette Silt hydrogeologic unit is generally equivalent to the Willamette Silt, deposited throughout much of the Willamette Lowland by late Pleistocene glacial-outburst floods. The unit extends over about 1,200 mi^2 and ranges in thickness from 0 to more than 130 ft (fig. 14). Except for the Portland Basin, the flood deposits consist primarily of silt and fine sand of relatively uniform lithology. The Willamette Silt unit is considered a distinct regional hydrogeologic unit because the silt overlies the Willamette aquifer and there are significant hydrologic and lithologic differences between the two units. In the Tualatin Basin where the Willamette aquifer is absent, the Willamette Silt is included with the Willamette confining unit, and therefore, the Willamette Silt unit is not delineate there. The Willamette Silt unit includes essentially a the fine-grained deposits above the Willamette aquife Therefore, the mapped unit may, in places, also includ some pre-flood sand and silt of local fluvial origin, addition to flood-deposited sediment.

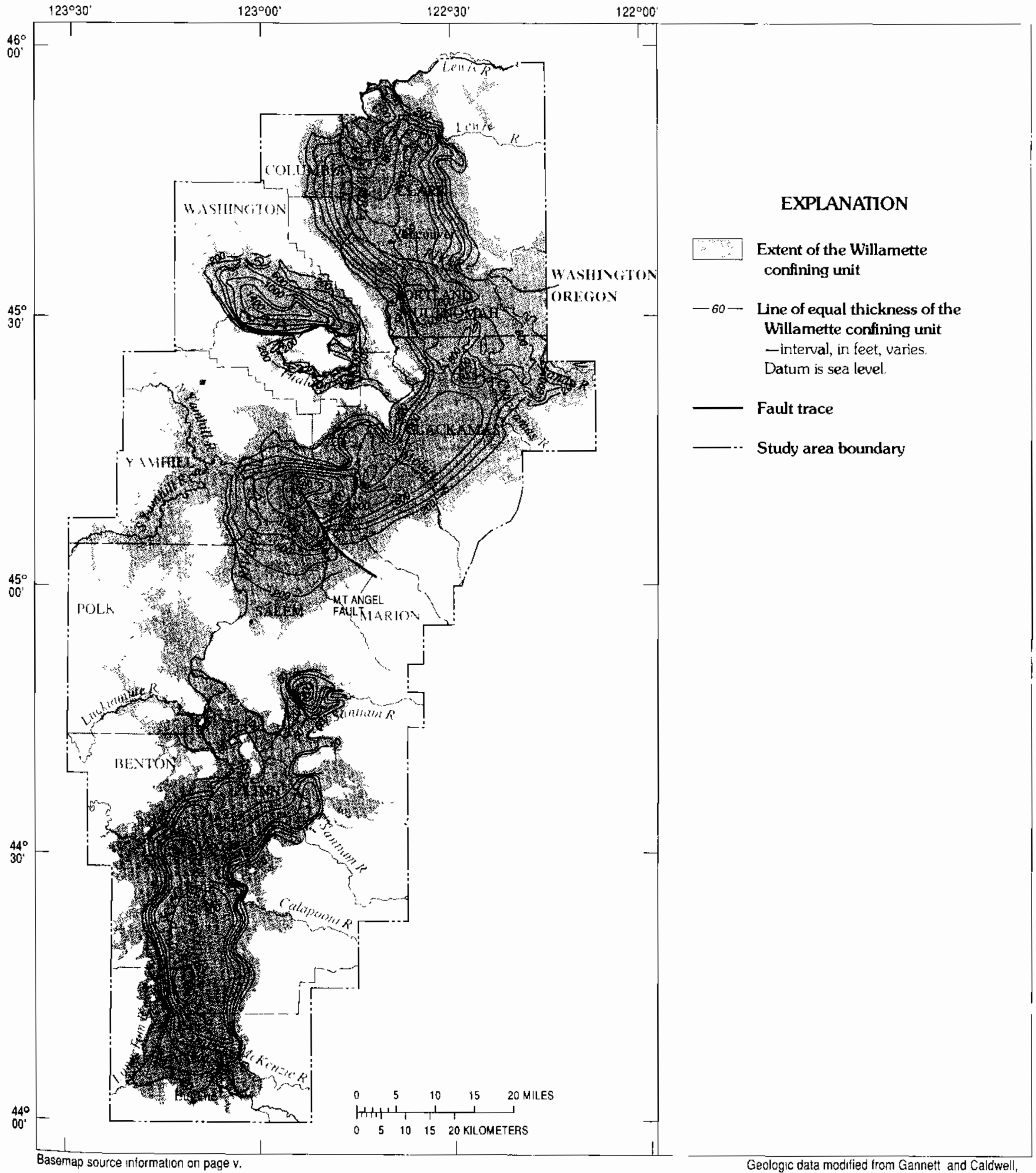

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FIGURE 12.—Extent and thickness of the Willamette confining unit.

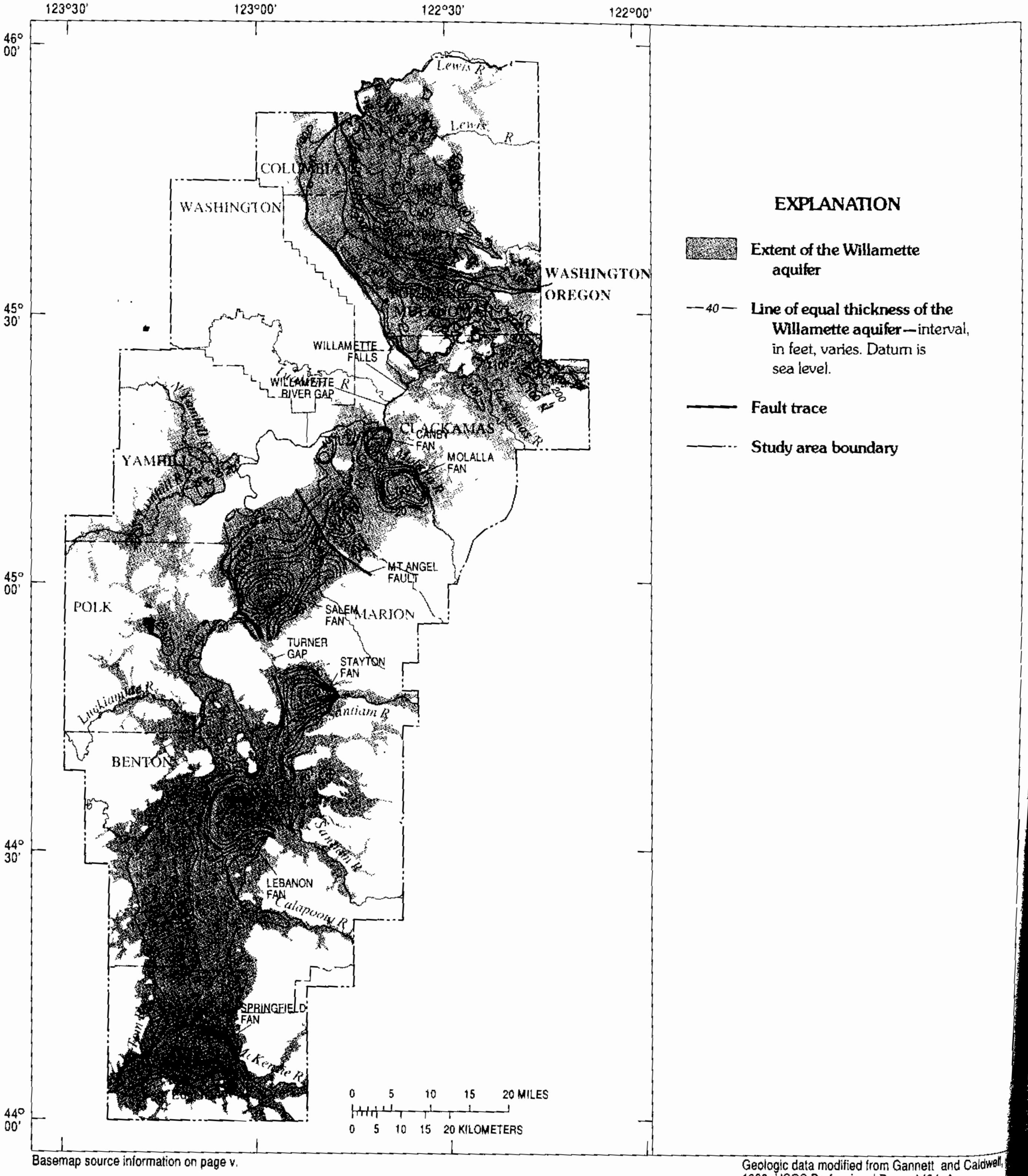

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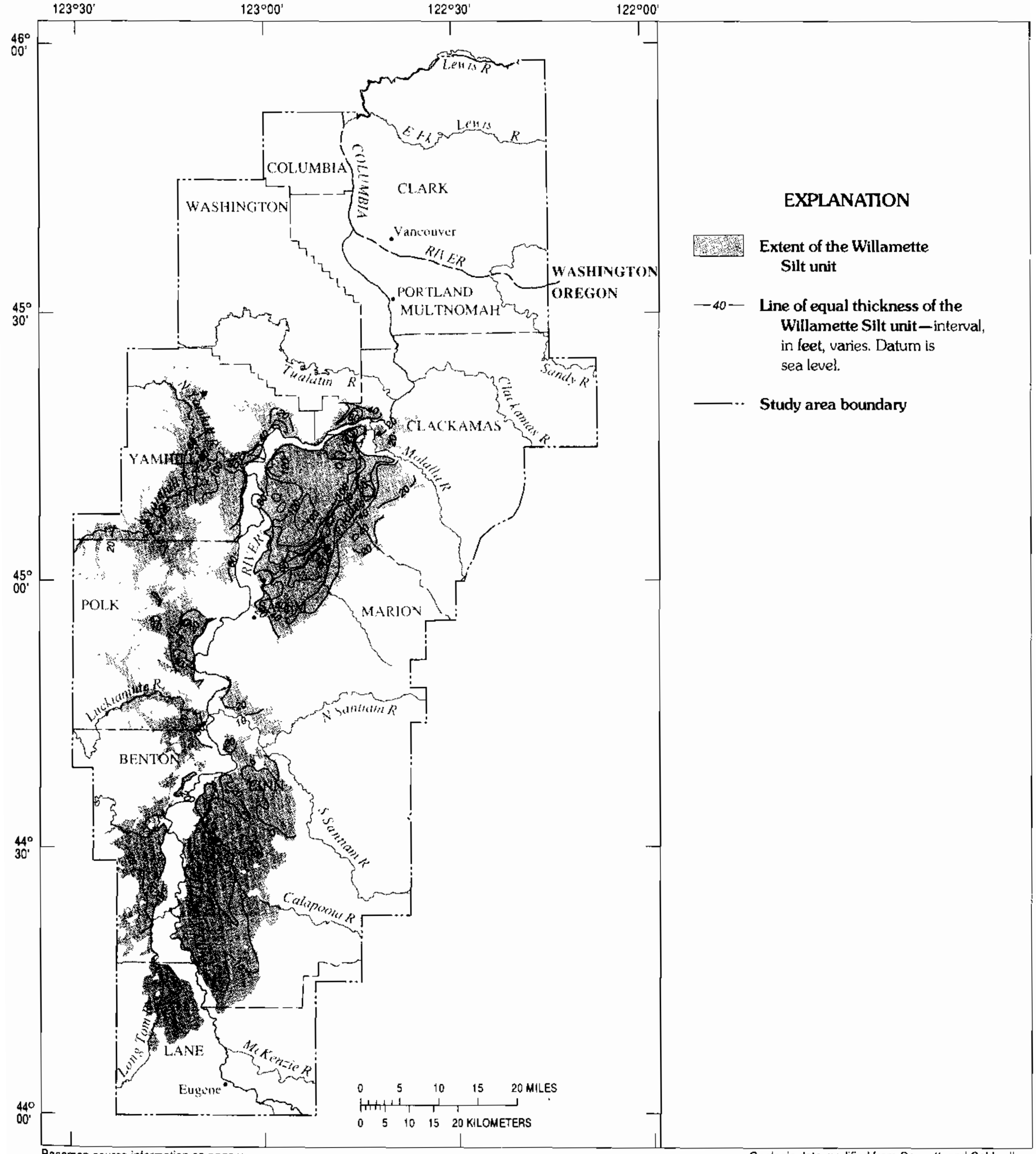
FIGURE 13.—Extent and thickness of the Willamette aquifer.



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Geologic data modified from Gannett and Caldwell, 1998, USGS Professional Paper 1424-A.

FIGURE 14.—Extent and thickness of the Willamette Silt unit.

GEOMETRY OF REGIONAL HYDROGEOLOGIC UNITS

The extent, thickness, and juxtaposition of the regional hydrogeologic units vary between the four basins in the Willamette Lowland. The differences are due primarily to variations in the origins of the basins, the regional tectonics, and the sources of sediment. An understanding of the geometry of each of the hydrogeologic units is important for the assessment of water availability. The geometry of each unit in each basin is described in the four sections that follow.

PORTLAND BASIN

The Columbia River basalt aquifer, the Willamette confining unit, and the Willamette aquifer occur in the Portland Basin. Because of the influence of the Columbia River, the geometry and lithology of the Willamette confining unit and Willamette aquifer in the Portland Basin differ from elsewhere in the Willamette Lowland.

The Columbia River basalt aquifer underlies most of the Portland Basin, and its upper surface forms a deep bowl-like depression (fig. 11); the altitude of the upper surface of the basalt is as deep as 1,600 ft below sea level in the center of the basin. The basalt aquifer is as much as 1,000 ft thick beneath the Portland Basin (Trimble, 1963) and thins out against the underlying basement confining unit near the northeastern margin. The Columbia River Basalt Group, which comprises the Columbia River basalt aquifer, extends beyond the Willamette Lowland east through the Cascade Range and northwest into the Coast Range (fig. 10). Along the western margin of the Portland Basin, the Columbia River basalt aquifer is exposed along a faulted, asymmetric anticline that forms the Tualatin Mountains (Beeson and others, 1989a,b). A major fault, known as the Portland Hills fault, has been mapped in the basin along the edge of this anticline (Beeson and others, 1991). Little is known about the relief on the bottom of the Columbia River basalt aquifer in the Portland Basin.

The Willamette confining unit also underlies most of the Portland Basin and is as much as 1,400 ft thick (fig. 12). Sediments contained in this unit have been described as mudstone, siltstone, claystone, and very fine sandstone (Trimble, 1963); and as siltstone and fine- to medium-grained sand, with local clay, water-laid ash, and minor gravelly interbeds (Swanson and others, 1993). In the Portland Basin, the Willamette confining unit generally corresponds to the lower sedimentary subsystem defined by Swanson and others (1993) and includes rocks assigned to the Sandy River Mudstone (Trimble, 1963). The mapped confining unit within the basin includes locally extensive coarse-grained sediments that have been tapped by numerous wells. Where the Columbia River debouches into the Portland Basin, sediment in the upper part of the Willamette confining unit grades laterally into a sequence of silty to gravelly sand locally named the "sand and gravel aquifer" (Hartford and McFarland, 1989; Swanson and others, 1993). This sand and gravel facies underlies an area of about 120 mi^2, averages 50 ft in thickness, and is locally more than 200 ft thick. The unit appears to be the thickest near the present channel of the Columbia River. Additionally, a layer of sand and basaltic conglomerate, averaging 100 to 200 ft in thickness, occurs in the upper part of the Willamette confining unit in the southern part of the Portland Basin. This unit, locally named the Troutdale sandstone aquifer, thins toward the west and northwest and grades into fine-grained sediments near the center of the basin (Swanson and others, 1993).

The Willamette aquifer in the Portland Basin includes the basin-filling deposits above the Willamette confining unit and generally ranges in thickness from about 100 ft to 400 ft, but locally is more than 600 ft thick (fig. 13). The aquifer generally corresponds to the upper sedimentary subsystem of Swanson and others (1993), which consists of their Troutdale gravel aquifer and unconsolidated sedimentary aquifer. The Troutdale gravel aquifer primarily consists of poorly to moderately cemented gravel in a matrix of sand, and conglomerate and sandstone (Swanson and others, 1993), and was deposited by the Columbia River and streams from the Cascade Range. The unconsolidated sedimentary aquifer consists of silt, sand, and gravel of glacial-outburst flood origin, Holocene alluvial deposits, terrace deposits along present drainages, and glacial outwash in small basins in northern Clark County, Washington.

The top of the Willamette aquifer coincides with land surface in that area because the Willamette aquifer includes the uppermost basin-fill units in the Portland Basin. Although alluvial-fan morphology is not apparent from the thickness of the Willamette aquifer in the Portland Basin (fig. 13), discharge and drainage-basin characteristics of the Clackamas River indicate that an extensive alluvial fan probably developed in the southeastern part of the basin. However, because of the overwhelming ability of the Columbia River to redistribute sediment in the basin, any fan morphology may have been altered beyond recognition.

TUALATIN BASIN

The Columbia River basalt aquifer and the Willamette confining unit are the only regional hydrogeologic units above the basement confining unit in the Tualatin Basin. The Columbia River basalt aquifer underlies the entire basin, and its upper surface forms a sediment-filled, bowl-like depression similar to that of the Portland Basin; the altitude of the top of the basalt is about 1,200 ft below sea level in the center of the basin (fig. 11). The aquifer is up to 1,000 ft thick in the Tualatin Basin (Hart and Newcomb, 1965) and thins out in the Coast Range foothills north and east of the Tualatin Basin; however, as previously described, it continues across intervening structures to the east into the Portland Basin and to the south into the central Willamette Valley. Two major faults, the Helvetia and Beaverton faults, have been mapped in the Tualatin Basin (fig. 10); seismic reflection profiles show these faults offset the Columbia River basalt aquifer (Yeats and others, 1991).

In the Tualatin Basin, the entire basin-fill section consists primarily of silt and clay, has only minor sand and gravel, and has been assigned to the Willamette confining unit. The unit has a maximum thickness of more than 1,400 ft (fig. 12). The confining unit includes sediments that were previously mapped as Troutdale Formation and Willamette Silt by Schlicker and Deacon (1967) and as undifferentiated valley fill by Hart and Newcomb (1965). Although minor sand and gravel deposits can be mapped in places within the Willamette confining unit, the individual deposits are not mappable on a regional scale because they are thin, laterally discontinuous, and occur over a wide range of depths. The top of the Willamette confining unit corresponds to land surface in the Tualatin Basin.

CENTRAL WILLAMETTE VALLEY

All five hydrogeologic units occur in the central Willamette Valley. The Columbia River basalt aquifer underlies the entire central Willamette Valley, except for small areas along the far eastern margin, where it thins out against the underlying basement confining unit. As in the Portland and Tualatin Basins, the basalt crops out along the margins of the basin and dips toward the center to form a roughly bowl-shaped depression. The top of the basalt is as much as 1,600 ft below sea level in the deepest part of the basin (fig. 11). The thickness of the Columbia River basalt aquifer varies throughout the central Willamette Valley, ranging from about 300 ft to as much as 600 ft. Several faults have been mapped in the central Willamette Valley, some of which offset the aquifer, and numerous other faults have been mapped in the uplands surrounding the basin where the aquifer crops out (fig. 10). According to Werner (1990), the aquifer is offset by as much as 800 ft by the northwest-trending Mount Angel fault in the southeastern part of the basin (fig. 11). A parallel structure with similar movement may exist several miles to the northeast of the Mount Angel fault (Gannett and Caldwell, 1998).

In the central Willamette Valley, the Willamette confining unit reaches a maximum thickness of about 1,600 ft (fig. 12). Sediments in the unit have been described as "thick layers of dark-gray to blue clay and shale separated by thin layers of sand and fine gravel, generally less than 5 feet thick" (Price, 1967a, p. 19). These sediments have been assigned both to the Sandy River Mudstone (Price, 1967a) and to the lower Troutdale Formation (Hampton, 1972). The thickness of the Willamette confining unit was not mapped in the Yamhill River Valley on the west side of the central Willamette Valley because the base could not be identified from well logs, but the unit is probably less than 100 ft thick in this area (Gannett and Caldwell, 1998). As elsewhere in the Willamette Lowland, potentially productive coarse-grained interbeds occur within the Willamette confining unit, but they generally are not mappable with the existing information from well logs. However, a tongue of sand and gravel about 10 to 30 ft thick and situated at about 80 to 100 ft below sea level extends north from the lower part of the Salem fan into the Willamette confining unit (fig. 9). This interbed is an important aquifer in the French Prairie area (fig. 1), is hydraulically connected to the Willamette aquifer, and is thus considered to be part of the Willamette aquifer (although it was not included in the aquifer thickness mapped on figure 13).

The Willamette aquifer in the central Willamette Valley ranges in thickness from 0 to more than 200 ft, and contains three major alluvial fans—the Salem fan, the Molalla fan, and the Canby fan (fig. 13). The largest of these fans, the Salem fan, occurs in the southern part of the central valley. The morphology of this fan indicates that most of the sediment was derived from streams entering from the south through a gap in the Columbia River Basalt Group. The Salem fan is 6 to 8 mi wide and forms a gravel deposit as much as 200 ft thick (fig. 13). In the southern part of the Salem fan, the Willamette confining unit is absent, and the Willamette aquifer directly overlies the Columbia River basalt aquifer (fig. 9). The northeastern part of the Salem fan merges with a thick section of gravel, immediately southwest of Mount Angel, that was probably deposited by a small creek entering the lowland from the east.

The Mount Angel fault affected the geometry of the Salem fan (fig. 13). The Willamette aquifer is much thicker on the downdropped, south side of this structure and thins abruptly to the north across the fault zone.

More rapid subsidence of the basin on the south side of this structure probably localized drainages in that area during basin development. The effects of the Mount Angel fault are not apparent on the west side of the valley. The tongue of gravel extending north from the Salem fan crosses the projected trace of the fault with no apparent offset.

The Molalla fan is present where the Molalla River debouches into the Willamette Valley. This fan is 4 to 6 mi wide and forms a gravel deposit as much as 120 ft thick (fig. 13). The Molalla fan overlies several hundred feet of the Willamette confining unit.

The third fan, known as the Canby fan, occurs in the northern part of the basin, just south of the Willamette River gap. It is about 2 mi wide and forms a gravel deposit as much as 100 ft thick (fig. 13). The Canby fan is different from other gravel fans in the central and the southern Willamette Valley in that it was deposited by glacial-outburst floods and, therefore, occurs in the uppermost part of the basin-fill sequence along with the Willamette Silt. Flood water entering the central Willamette Valley from the Portland Basin had sufficient velocity to transport gravel: as the water entered the central Willamette Valley, its velocity decreased, allowing for deposition of the gravel. Flood sediment elsewhere in the valley consists primarily of silt and fine sand.

The Willamette aquifer was not mapped throughout the lowland. In the northwestern part of the central Willamette Valley, the aquifer was not mapped because the gravel deposits are thin and discontinuous, occur at various elevations, and do not represent a hydraulically continuous unit. Additionally, the geometry of the Willamette aquifer is complex northeast of the Mount Angel fault and south of the Molalla fan. This may be due to the effects of the fault or the presence of numerous small drainages that enter the valley in that area.

The Willamette Silt unit overlies most of the central Willamette Valley. The unit has a maximum thickness of about 130 ft near the center of the basin and generally thins toward the south and near the margins of the basin (fig. 14). The silt has been eroded along the modern flood plain of the Willamette River and now forms steep bluffs along the margin of the flood plain in the northern part of the basin. The silt also has been eroded from the valley floor—along the northeastern side of the Salem Hills—between the Turner gap and the Willamette River gap near Salem (fig. 2).

SOUTHERN WILLAMETTE VALLEY

In the southern Willamette Valley, all of the regional hydrogeologic units are present; however, the Columbia River basalt aquifer occurs only in the Stayton Subbasin (fig. 10), where it is overlain by the Willamette confining unit. Throughout the remainder of the valley, the Willamette confining unit overlies the basement confining unit, except beneath the upstream ends of the alluvial fans where the confining unit is absent (fig. 9). Both the Willamette aquifer and the Willamette Silt unit overlie the Willamette confining unit in the southern Willamette Valley.

The Willamette confining unit is thinner in the southern Willamette Valley than elsewhere in the Willamette Lowland and ranges from less than 20 to about 340 ft thick (fig. 12). Sediments in this unit are described as having a distinctly blue color and consisting of clay to silty clay, sandy clay and clayey silt, with occasional lenses of well sorted, unconsolidated medium to fine sand (Niem and others, CH2M-Hill, unpub. data, 1987). Frank (1973, 1974, 1976) assigned this sediment in the southern valley to either the older alluvium or the Eugene Formation. Differentiating fine-grained sediment of the Willamette confining unit from the underlying fine-grained marine sedimentary rocks was difficult using only information from water well logs. Therefore, the placement of contours for this unit on figure 12 may be less accurate in the southern Willamette Valley than elsewhere in the lowland.

The Willamette aquifer ranges from less than 20 ft to as much as 240 ft thick in the southern Willamette Valley and contains three large fans—the Springfield fan, the Lebanon fan, and the Stayton fan (fig. 13). The coarse-grained deposits of these fans generally overlie silt and clay of the Willamette confining unit. However, at the heads of these fans in the river valleys of the Cascade foothills, the fans grade into valley-train gravel deposits (locally more than 240 ft thick) that lie directly on the basement confining unit.

The Springfield fan, which is the southernmost of the three, was deposited by the ancestral Willamette and McKenzie Rivers. It forms a predominantly sand and gravel deposit as much as 240 ft thick and 8 to 9 mi wide (fig. 13). The Lebanon fan, deposited primarily by the South Santiam River, is about 8 to 10 mi wide and includes predominantly sand and gravel deposits that are as much as 140 ft thick (fig. 13). The Stayton fan, in the northeastern part of the southern valley, occupies the partly enclosed Stayton Subbasin (fig. 13). The North Santiam River, which enters the eastern part of the subbasin, created this alluvial fan, which abuts the opposite side of the subbasin formed by the Salem Hills. The Stayton fan is from 6 to 8 mi wide and has a maximum thickness of about 300 ft.

The Willamette aquifer is much thinner (averaging only about 20 to 40 ft thick) between the alluvial fans o the southern Willamette Valley (fig. 13) than in the centra Willamette Valley. The relatively thin gravel between th fans corresponds, in part, to the Linn gravel and genera ly is at or near the top of the pre-flood, basin-fill sectio