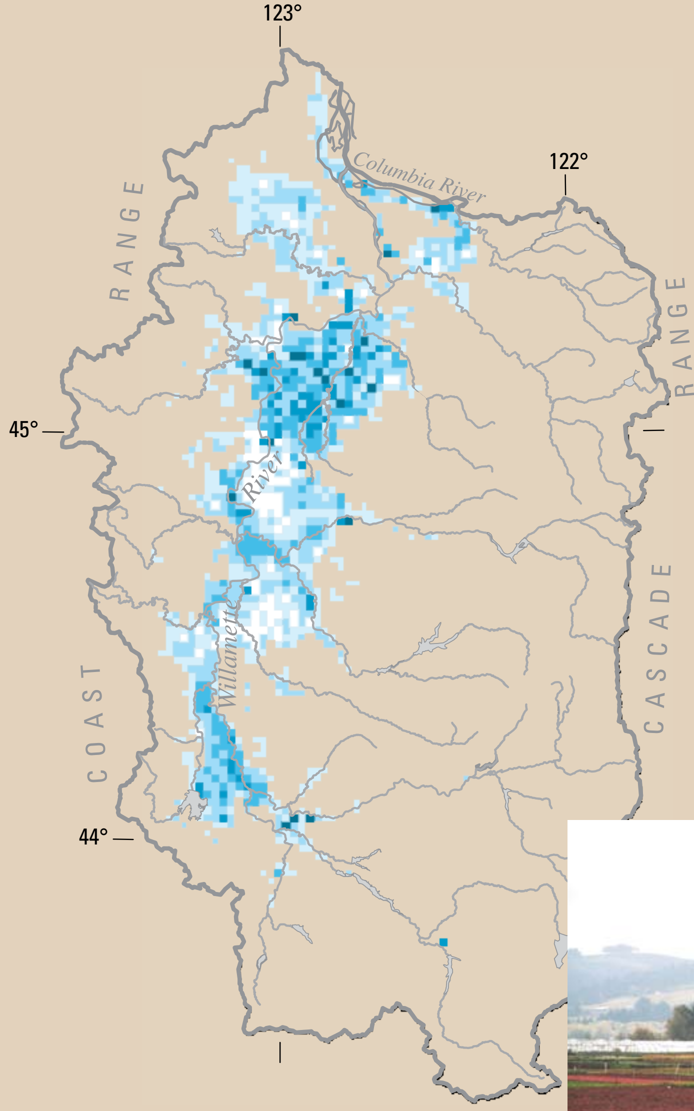
Prepared in cooperation with the Oregon Water Resources Department

Ground-Water Hydrology of the Willamette Basin, Oregon



Scientific Investigations Report 2005–5168

U.S. Department of the Interior
U.S. Geological Survey

Front cover: Irrigated nursery stock (foreground) and uplands underlain by Columbia River Basalt Group (background), central Willamette Basin, Oregon. Photograph by Karl Wozniak.

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By Terrence D. Conlon, Karl C. Wozniak, Douglas Woodcock, Nora B. Herrera, Bruce J. Fisher, David S. Morgan, Karl K. Lee, and Stephen R. Hinkle

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Plate [in pocket]

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Conversion Factors

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

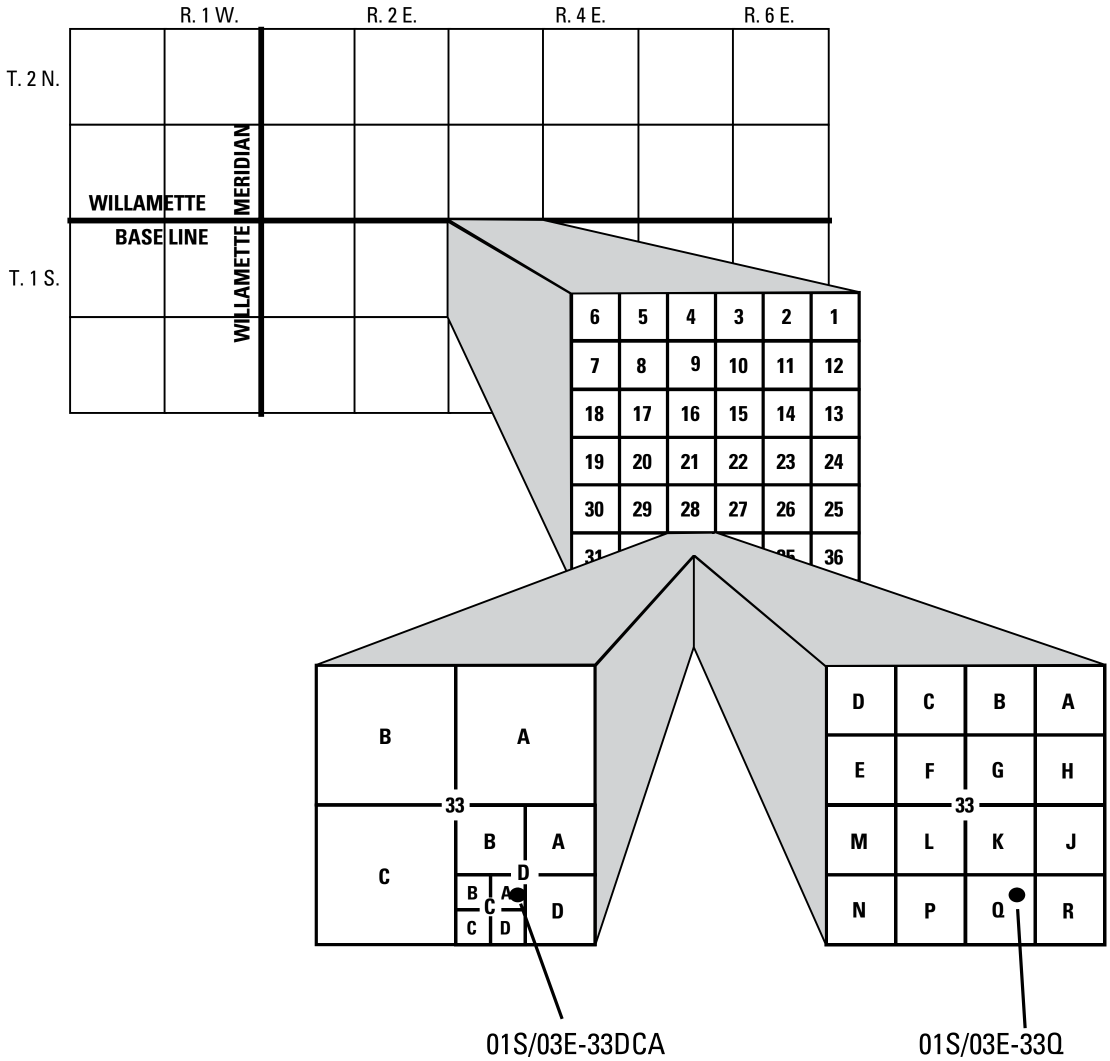
°C=(°F-32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)."

Altitude, as used in this report, refers to distance above the vertical datum.

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Base map composited from U.S. Geological Survey digital line graphs and other digital information. Universal Transverse Mercator projection, zone 10 1927 North American Datum. Longitude of Central Meridian: -123.000000. Latitude of Projection Origin: 0.000000. False Easting: 500000.000000. False Northing: 0.000000.



Well- and Spring-Location System

The system used for locating wells and springs in this report is based on the rectangular system for subdivision of public land. The State is divided into 36 square-mile townships numbered according to their location relative to the east-west Willamette baseline and a north-south Willamette meridian. The position of a township is given by its north-south “Township” position relative to the baseline and its east-west “Range” position relative to the meridian. Each township is divided into 36 sections approximately 1 square mile (640-acre) in area and numbered from 1 to 36. For example, a well designated as 01S/03E-33DCA is located in Township 1 south, Range 3 east, section 33. The letters following the section number correspond to the location within the section; the first letter (D) identifies the quarter section (160 acres), the second letter (C) identifies the quarter-quarter section (40 acres), and the third letter (A) identifies the quarter-quarter-quarter section (10 acres). Thus, well 33DCA is located in the NE quarter of the SW quarter of the SE quarter of section 33. When more than one designated well occurs in the quarter-quarter-quarter section, a serial number is appended. For some wells that were field located during previous USGS and OWRD studies, a different system of letters following the section number was used for the location within the section. This system assigns a letter to one of 16 quarter-quarter sections (40 acres) that divide the section. The location 33DCA would correspond to the location 33Q. When more than one designated well occurs in the quarter-quarter section, a serial number is appended.

Ground-Water Hydrology of the Willamette Basin, Oregon

By Terrence D. Conlon, Karl C. Wozniak, Douglas Woodcock, Nora B. Herrera, Bruce J. Fisher, David S. Morgan, Karl K. Lee, and Stephen R. Hinkle

Abstract

The Willamette Basin encompasses a drainage of 12,000 square miles and is home to approximately 70 percent of Oregon's population. Agriculture and population are concentrated in the lowland, a broad, relatively flat area between the Coast and Cascade Ranges. Annual rainfall is high, with about 80 percent of precipitation falling from October through March and less than 5 percent falling in July and August, the peak growing season. Population growth and an increase in cultivation of crops needing irrigation have produced a growing seasonal demand for water. Because many streams are administratively closed to new appropriations in summer, ground water is the most likely source for meeting future water demand. This report describes the current understanding of the regional ground-water flow system, and addresses the effects of ground-water development.

This study defines seven regional hydrogeologic units in the Willamette Basin. The highly permeable High Cascade unit consists of young volcanic material found at the surface along the crest of the Cascade Range. Four sedimentary hydrogeologic units fill the lowland between the Cascade and Coast Ranges. Young, highly permeable coarse-grained sediments of the upper sedimentary unit have a limited extent in the floodplains of the major streams and in part of the Portland Basin. Extending over much of the lowland where the upper sedimentary unit does not occur, silts and clays of the Willamette silt unit act as a confining unit. The middle sedimentary unit, consisting of permeable coarse-grained material, occurs beneath the Willamette silt and upper sedimentary units and at the surface as terraces in the lowland. Beneath these units is the lower sedimentary unit, which consists of predominantly fine-grained sediments. In the northern part of the basin, lavas of the Columbia River basalt unit occur at the surface in uplands and beneath the basin-fill sedimentary units. The Columbia River basalt unit contains multiple productive water-bearing zones. A basement confining unit of older marine and volcanic rocks of low permeability underlies the basin and occurs at land surface in the Coast Range and western part of the Cascade Range.

Most recharge in the basin is from infiltration of precipitation, and the spatial distribution of recharge mimics the distribution of precipitation, which increases with elevation. Basinwide annual mean recharge is estimated to be 22 inches. Rain and snowmelt easily recharge into the permeable High Cascade unit and discharge within the High Cascade area. Most recharge in the Coast Range and western part of the Cascade Range follows short flowpaths through the upper part of the low permeability material and discharges to streams within the mountains. Consequently, recharge in the Coast and Cascade Ranges is not available as lateral ground-water flow into the lowland, where most ground-water use occurs. Within the lowland, annual mean recharge is 16 inches and most recharge occurs from November to April, when rainfall is large and evapotranspiration is small. From May to October recharge is negligible because precipitation is small and evapotranspiration is large.

Discharge of ground water is mainly to streams. Ground-water discharge is a relatively large component of flow in streams that drain the High Cascade unit and parts of the Portland Basin where permeable units are at the surface. In streams that do not head in the High Cascade area, streamflow is generally dominated by runoff of precipitation. Ground-water in the permeable units in the lowland discharges to the major streams where there is a good hydraulic connection between aquifers and streams. Ground-water discharge to smaller streams, which flow on the less permeable Willamette silt unit, is small and mostly from the Willamette silt unit.

Most ground-water withdrawals occur within the lowland. Irrigation is the largest use of ground water, accounting for 240,000 acre feet of withdrawals, or 81 percent of annual ground-water withdrawals. Most withdrawals for irrigation occur from March to October and are largely from the upper and middle sedimentary unit in the central Willamette and southern Willamette Basins. Lesser amounts of ground water are withdrawn from the Columbia River basalt and lower sedimentary units. Withdrawals from the basement confining unit are a small percentage of total withdrawals. No significant water is withdrawn from the Willamette silt unit.

The effect of ground-water withdrawals on streamflow in the lowland is small for many streams because there is a poor hydraulic connection between streams that flow on the less permeable Willamette silt unit and the productive middle sedimentary unit. Withdrawals from wells open to the middle and upper sedimentary units capture ground water that would otherwise discharge to the large streams that have an efficient hydraulic connection to the upper sedimentary unit.

In the lowland, average annual water levels and the direction of ground-water flow are unchanged from predevelopment conditions in 1935. Seasonal water-level fluctuations outside the central Willamette Basin are similar to predevelopment fluctuations. In the central Willamette Basin, seasonal water-level fluctuations have increased by as much as 55 feet because of increased summer pumpage, but in most areas, the

water levels return to their historic winter high levels. In some areas, water levels vary on a decadal scale in response to climatic trends, but these changes are small compared to seasonal fluctuations.

Long-term water-level declines are observed in wells open to the Columbia River basalt unit in areas with concentrated pumping. Declines as great as 6 feet per year have occurred in some areas.

Introduction

Background and Study Objectives

The Willamette Basin (fig. 1) is home to about two-thirds of the residents of Oregon and has one of the fastest growing populations in the State. Census figures indicate 2.4 million people lived in the Willamette Basin, an increase of 0.4 million, or 20 percent, since 1990 (U.S. Census Bureau, 2003). The Willamette Basin is also a major agricultural area, accounting for over 50 percent of Oregon's crop sales (Oregon Agricultural Statistics Service, 2001). Rapid population growth and the need for irrigation have increased the demand for water within the basin. The principal sources of water available to meet these demands are streams, reservoirs, and ground water.

The Oregon Water Resources Department (OWRD) allocates surface and ground water with a permit system based on the doctrine of prior appropriation. Because of competing demands for municipal, industrial, irrigation, and instream (pollution abatement and fish habitat) uses, many streams in the basin are administratively closed to additional appropriation in the summer, when demand is high and streamflow is low. Ground water is the only readily available resource to satisfy new demands in many areas. Various factors limit the capacity of the ground-water system to meet these demands including (1) potential depletion of streamflow by ground-water withdrawals, (2) large seasonal and long-term declines in ground-water levels, (3) low-permeability aquifers that are suitable for low-demand uses only, and (4) natural water-quality problems that affect human health.

Prior to this study, the information and tools to quantify these limiting factors were inadequate. To address this deficiency, the U.S. Geological Survey (USGS) and the OWRD began a cooperative study in 1996. The main objectives of this study were to assess the regional ground-water system and to develop quantitative tools that can be used to support water-resources management decisions. This report is one in a series that presents the results of the study.

Previous publications from the study have documented the distribution of arsenic in ground water (Hinkle and Polette, 1999), compiled water levels, ground-water chemistry, and geophysical logs (Orzol and others, 2000), described the origin, extent and thickness of permeable sediments in the floodplain of the major tributaries of the basin (O'Connor and others 2001), estimated ground-water recharge and the exchange of water between aquifers and streams (Lee and Risley, 2002), and estimated ground-water discharge to streams using heat as a tracer (Conlon and others, 2003).

Piper (1942) completed the earliest comprehensive study of hydrogeology in the Willamette Basin, and laid the foundation for subsequent investigations, which include qualitative water-supply assessments by Brown (1963), Hogenson and Foxworthy (1965), Hart and Newcomb (1965), Price (1967a, 1967b), Foxworthy (1970), Hampton (1972), Frank (1973, 1974, 1976), Frank and Collins (1978), Gonthier (1983), and Leonard and Collins (1983). Much of this earlier work was synthesized by McFarland (1983) into a larger framework that defined and described the regional aquifer units of western Oregon.

In the late 1980s, an investigation was conducted by the U.S. Geological Survey to quantify ground-water resources of the Portland Basin. Results were published in reports that describe the geologic framework (Swanson and others, 1993), ground-water pumpage (Collins and Broad, 1993), ground-water recharge (Snyder and others, 1994), and ground-water flow system (McFarland and Morgan, 1996) in the basin. In addition, a numerical model was constructed to simulate ground-water flow (Morgan and McFarland, 1996).

A synthesis of the hydrogeology of the Willamette lowland was conducted in the early 1990s as part of the Regional Aquifer-System Analysis (RASA) program of the U.S. Geological Survey (Vacarro, 1992). The main products are an extensive bibliography of the hydrogeology of the Willamette Basin (Morgan and Weatherby, 1992), a comprehensive description of the geologic framework (Gannett and Caldwell, 1998) and a description of regional hydrogeologic units (Woodward and others, 1998).

Purpose and Scope

The purpose of this report is to provide a conceptual framework of the ground-water flow system in the Willamette Basin that will help resource managers evaluate the impacts of ground-water-management decisions. The report integrates information from previous studies and data collected during the current study.

The study was divided into a regional phase to understand the ground-water flow and ground-water budget for the entire Willamette Basin and a focused phase to evaluate temporal changes in the ground-water flow in the central Willamette Basin (pl. 1). Although the study covered the entire Willamette Basin, the scarcity of well data in the Coast and Cascade Ranges limited the scope of a detailed analysis to the Willamette lowland.

Regional scale data, including ground-water levels, geophysical logs, stream seepage (gains and losses), and ground-

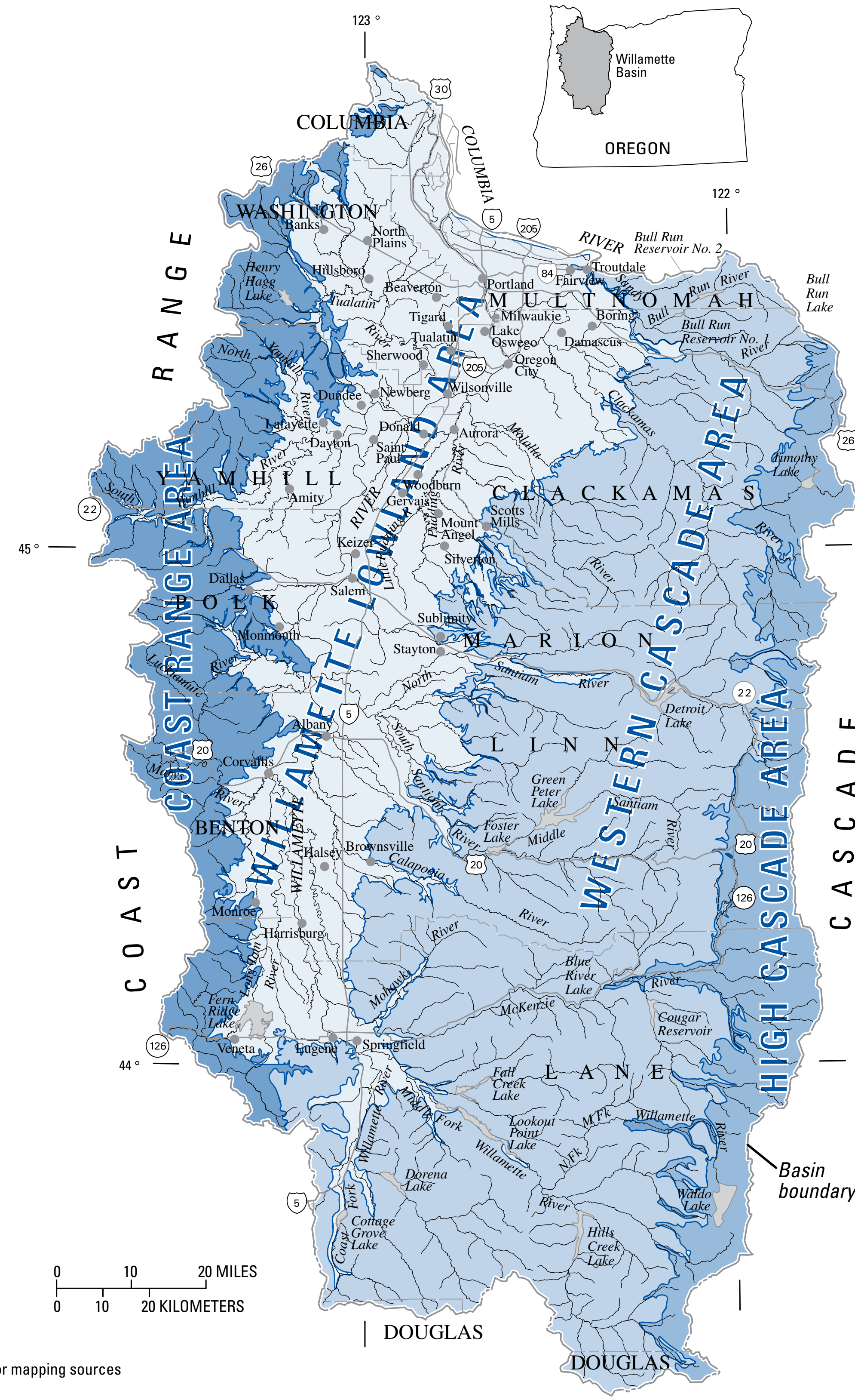


Figure 1. Location of Willamette Basin, Oregon and major geographic and cultural features.

water chemistry, were collected from 1996 to 2003, with an emphasis on the period between 1996 and 1997. Focused data collection in the central Willamette Basin between 1998 and 2003 included ground-water levels, stream seepage, aquifer tests, and water temperature of streams and ground water.

Study Area

The study area (fig. 1) includes the Willamette and Sandy River drainage basins in northwestern Oregon. The combined drainage area of the two basins is referred to as the Willamette Basin in this report. The study area encompasses about 12,000 square miles between the crests of the Coast Range on the west and the Cascade Range on the east. It is bounded on the south by the convergence of the Coast and Cascade Ranges and on the north by the Columbia River.

The Clackamas, North and South Santiam, McKenzie, and Middle Fork Willamette Rivers are the major tributaries to the Willamette River. These large streams drain the Cascade Range. Smaller streams in the Cascade and Coast Ranges also flow into the Willamette River, which flows through the lowland to the Columbia River at the northern edge of the study area.

The Willamette Basin is bordered on the west by the deeply incised Coast Range, where elevations range from 1,000 to 4,000 ft (feet). The east side of the basin is bounded by the Cascade Range, which includes the older, more weathered and deeply incised Western Cascade area, where elevations range from 1,000 to 6,000 ft, and the younger High Cascade area, where elevations range from 4,000 ft near mountain passes to 10,000 ft at the summit of volcanic peaks along the crest of the range. Between the Coast and Cascade Ranges is a lowland, approximately 120 mi (miles) long and 20 mi wide, where most of the population, industry, and agriculture occurs. Elevations within the lowland plain are near sea level at Portland and gently increase to about 400 ft near Eugene. Uplands of bedrock that reach elevations of 1,500 ft divide the lowland into the Portland, Tualatin, central Willamette, Stayton, and southern Willamette Basins (pl. 1).

The Willamette Basin is characterized by cool, wet winters and warm, dry summers. Precipitation, mostly from winter storms moving eastward from the Pacific Ocean, varies with elevation. Mean annual precipitation (fig. 2) ranges from 40 to 130 in (inches) (mostly rain) in the Coast Range, approximately 40 in (rain) in the lowland, 50 to 100 in (mostly rain) in the Western Cascade area, and up to 130 in (rain and snow) at crest of the Cascade Range. Heavy snowfall occurs in winter in the Cascade Range, resulting in permanent snowfields and glaciers on the highest peaks. About 80 percent of the annual precipitation falls from October through March, but less than 5 percent falls in July and August (Wentz and others, 1998). Precipitation at Salem was above average for water years 1995–99 and 2002, average for 2003, and below average from 2000–2001. An especially dry water year was 2001, when precipitation was approximately 50 percent of average.

Mean monthly temperatures in the lowland range from 39 degrees F (Fahrenheit) in January to 68 degrees F in August. In the Coast Range and Western Cascade area, mean monthly temperatures range from 37 degrees F in January to 64 degrees F in August. The mean monthly temperature in the High Cascade area is 28 degrees F in January and 57 degrees F in August.

Approximately 70 percent of the Willamette Basin is forested, including most of the Coast and Cascade Ranges (Pacific Northwest Ecosystem Research Consortium, 2002). Agricultural land encompasses 20 percent of the study area and is generally restricted to the lowland. The remaining land is urban, covered grasslands, water, or snow. Major population centers are the metropolitan areas of Portland, Salem-Keizer, Corvallis, and Eugene-Springfield. Of these communities, Springfield and Keizer rely solely on ground water. Salem, Portland, and some suburban Portland communities use ground water to supplement surface-water supplies during summer. Many smaller communities rely on ground water.

Agricultural crops in the Willamette Basin account for 62 percent of Oregon's total crop sales and include grass seed, wheat, hay, oats, clover and vetch seed, sweet corn, filberts, snap peas, mint, berries, hops, vineyards, and nursery stock. Historically, crops, such as wheat, that do not require irrigation were cultivated in the lowland. As markets and technology evolved, high-value crops that require irrigation became more common. Because surface-water irrigation is limited to fields adjacent to streams, much of the lowland is irrigated with ground water. Irrigation with ground water is increasing adjacent to many smaller streams because of low streamflow and poor surface-water quality in the summer. Irrigation canals are not widely used, except in the Stayton Basin.

Approach

The ground-water flow system in the Willamette Basin was characterized by (1) reviewing existing geologic and hydrologic reports, (2) locating wells for geologic and ground-water level information, (3) compiling and collecting water-level information to evaluate ground-water flow directions and water-level trends, and (4) collecting other hydrologic data to evaluate recharge, ground-water flow paths, and exchanges between surface and ground waters. This report addresses these elements and supports the data needs for the development of computer models to simulate the ground-water flow system.

Data for approximately 6,000 wells located in previous studies and as part of this study were compiled (Orzol and others, 2000). A subset of about 1,200 wells provided information on subsurface geology, water chemistry, and ground-water levels. Subsurface geology was interpreted from geophysical logs collected in 16 wells, ground-water age was estimated in 21 wells using chlorofluorocarbons, and water levels were measured in 687 wells. Wells referred to in this report are

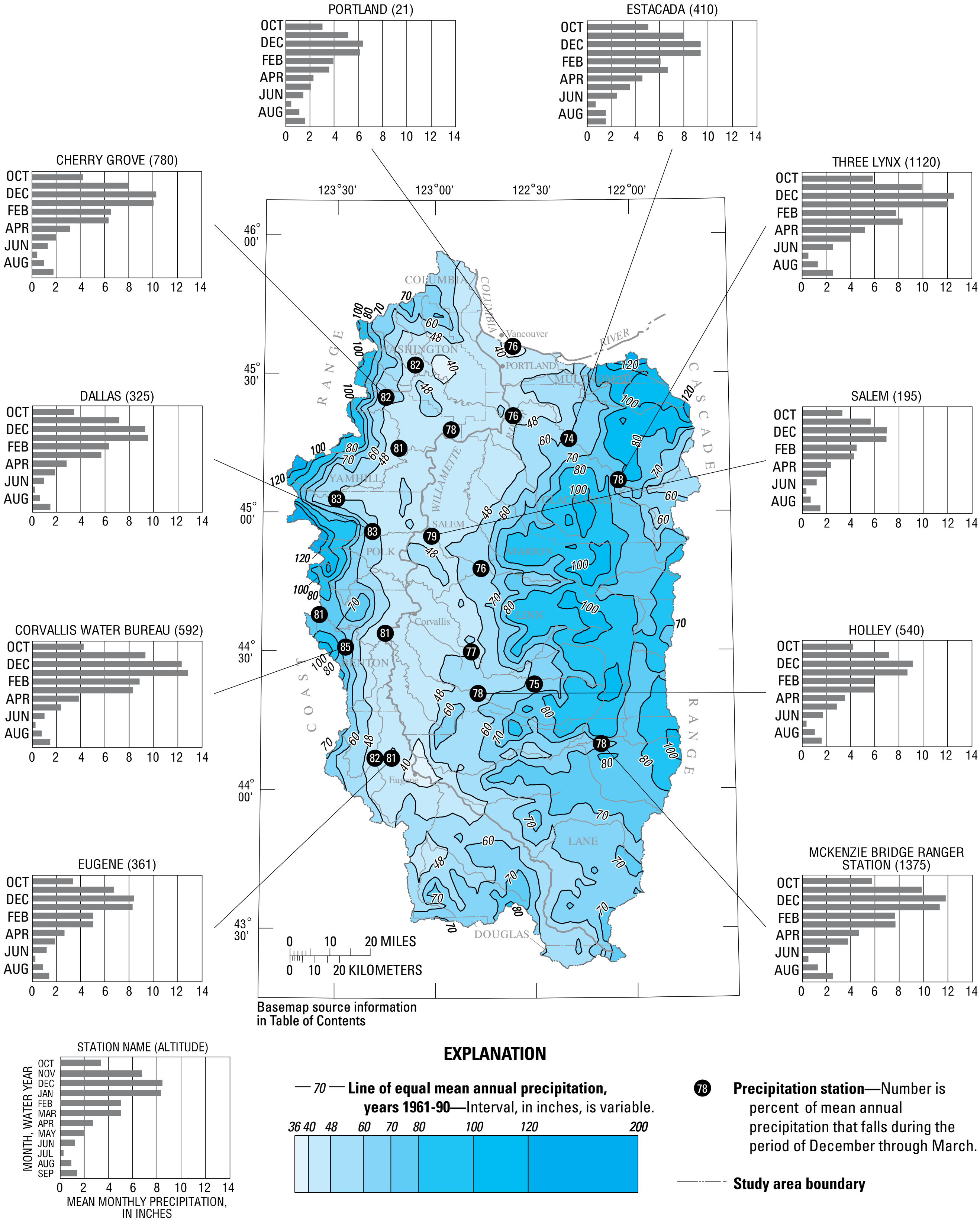


Figure 2. Mean annual and mean monthly precipitation, Willamette Basin, Oregon (modified from Woodward and others, 1998).

listed by location in Appendix A and correlated to USGS and OWRD identifiers.

Several observation-well networks were established during the study to evaluate the ground-water flow system. During a 2-week period in November 1996, water levels were measured in approximately 470 wells to construct ground-water level maps and to infer horizontal and vertical ground-water flow directions. To understand the temporal dynamics of the flow system, water levels were collected every 2 hours in 48 unused wells equipped with data loggers. An additional 12 wells were instrumented with data loggers for shorter periods to measure responses to aquifer tests and other short-term hydrologic stresses. A second network of 118 wells, measured bimonthly over periods ranging from 1 to 6 years, was established to supplement the continuous-recorder network. In addition to these wells, the OWRD maintains a network of about 51 long-term observation wells that are generally measured 4 times per year. Historic water levels, with periods of record ranging from 1 to 70 years, are also available for several hundred inactive observation wells that were measured by the USGS or by OWRD between 1928 and 2000. Water-level data for most of these wells were published by Orzol and others (2000). Several aquifer tests conducted during the study were analyzed to estimate hydraulic properties of aquifers and confining units.

To evaluate the impacts of ground-water pumping on smaller streams, detailed information was collected at a site near Mount Angel, Oregon, adjacent to the Pudding River. This information is summarized by Iverson (2002).

The components of the hydrologic budget include recharge, evapotransporation, ground-water withdrawals, and discharge to streams. Recharge from precipitation and evapotranspiration from the unsaturated zone were estimated with watershed models (Lee and Risley, 2002). Evapotranspiration from the water table was estimated in the southern Willamette Basin where the water table is near land surface. Ground-water withdrawals for public use were based on measurements or estimates reported to OWRD. Industrial water use was estimated from water right records at OWRD. Irrigation withdrawals were estimated using LANDSAT images, crop-water-use estimates, and ground-water right information from OWRD. Recharge from surface water and ground-water discharge to surface water were estimated from seepage measurements (Lee and Risley, 2002), seepage meters and heat-tracing methods (Conlon and others, 2003).

Acknowledgments

The authors wish to thank the hundreds of landowners who allowed access to their wells. We especially acknowledge Charles Eder and Ron Johnson for granting permission to install piezometers on their land and six other landowners for allowing piezometers to be installed in streams adjacent to their land. The City of Mount Angel and Paul Kirsch generously allowed us to perform aquifer tests on their wells. Drillers, especially Steve Schneider of Schneider Equipment and Floyd Sippel of Sippel Well Drilling, are acknowledged for collecting drill cuttings and providing opportunities to obtain geophysical logs from water wells. Lastly, several individuals, notably Marvin Beeson and Terry Tolan, helped shape our interpretation of the hydrogeology by generously sharing their time and expertise. The passion for understanding the geology of the Columbia River Basalt Group demonstrated by Marvin Beeson, who passed away in 2004, will be missed.

Hydrogeologic Framework

The Willamette Basin is a topographic and structural trough that lies between the Coast Range and the Cascade Range (fig. 1). The basin lowland is divided into five sedimentary subbasins that are separated by local uplands of the Columbia River Basalt Group lavas. Stream drainages between the basins are restricted by narrow water gaps that cut into the Columbia River Basalt Group or older, low-permeability bedrock. Variations in the depositional histories of each subbasin have created hydrogeologic conditions that are distinct but broadly related by common features of the geologic history of the entire basin (Woodward and others, 1998). A general geologic history of the basin is presented below to provide a setting for understanding the main geologic controls on the ground-water hydrology of the basin. Detailed geologic histories can be found in Gannett and Caldwell (1998), O'Connor and others (2001), Yeats and others (1996), and Orr and others (1992).

The Coast Range is composed of uplifted Tertiary marine sedimentary rocks and related marine volcanic and intrusive rocks. The Cascade Range is an accumulation of volcanic lavas and debris erupted from continental volcanoes. Tertiary marine strata and older Cascade volcanic rocks interfinger at depth beneath the Willamette Valley to form the bedrock foundation of the lowland. During the initial formation of the Cascade Range, around 35–40 million years ago, the ancestral Pacific shoreline was located near the present foothills of the range at the eastern margin of the Willamette lowland (Orr and others, 1992). As the Cascade Range grew by the accumulation of volcanic debris, east-west compressive forces began to uplift the area currently occupied by the Coast Range and depress the area that is now the Willamette lowland. As this process continued, the valley gradually became isolated from the sea and began to accumulate sediments deposited by rivers draining the Cascade Range and the rising Coast Range. Around 16 to 14 million years ago, numerous large-volume lava flows of the Columbia River Basalt Group erupted from vents east of the Cascade Range, entered the northern valley through a gap in the Cascade Range, and flooded low-lying areas as far south as Salem (Beeson and others, 1989a). During and after the emplacement of the Columbia River basalt lavas, the Coast Range continued to rise and the Columbia River basalt lavas and underlying bedrock were distorted by faulting and folding to create five sedimentary subbasins that are separated by local uplands of basalt lava. From north to south, these are the Portland Basin, the Tualatin Basin, the central Willamette Basin, the Stayton Basin, and the southern Willamette Basin (pl. 1). The Stayton Basin is small and, unless mentioned specifically, is included in the southern Willamette Basin in this report. Fluvial and lacustrine sediments have subsequently filled these basins. Sediment thickness exceeds 1,400 ft in the Portland, Tualatin, and central Willamette Basins but is generally less than 500 ft in the Stayton and southern Willamette Basins (Gannett and Caldwell, 1998). After emplacement of the Columbia River Basalt Group, volcanic material continued to be produced from the Cascade Range and covered the lavas east of the lowland.

The bulk of the basin-fill sediments in the Willamette lowland consists of clays and silts that were deposited in low-energy depositional environments that included distal alluvial fans, low-gradient streams, and lakes (Gannett and Caldwell, 1998). Fine-grained deposits predominate in the western portions of the lowland and at depth. Coarse-grained sediments are largely restricted to the eastern side of the basin, where high-gradient streams draining the Cascade Range enter the valley lowland. Most of the coarse-grained, basin-fill deposits south of the Portland Basin were deposited in braided stream environments on alluvial fans and braid-plains that formed during the Pleistocene Epoch (Gannett and Caldwell, 1998; O'Connor and others, 2001). Alluvial fans are thickest on the eastern and southern flanks of the valley where major Cascade Range streams enter the valley lowland. Extensive deposits of coarse-grained sediments are not associated with streams that drain the Coast Range on the west side of the valley. This is particularly evident in the Tualatin Basin, where the bulk of the basin-fill sediments are fine-grained deposits eroded from local highlands within the basin (Wilson, 1997).

Between about 15,000 and 12,000 years ago, repeated glacial outburst floods from Glacial Lake Missoula swept down the Columbia River drainage and inundated the Willamette Basin with water up to elevations of 500 ft (O'Connor and others, 2001). As the flood waters exited the narrow reaches of the Columbia River gorge east of Portland, flood velocities subsided and a large delta of sand and gravel was deposited in the Portland Basin. Elsewhere in the Willamette Basin, lower velocity flood-waters formed temporary lakes that produced the extensive Willamette Silt beds in the area south of the Portland Basin. Following the deposition of the Willamette Silt, the Willamette River and its main Cascade tributaries established new floodplains by eroding steep-walled trenches through the silt. These modern floodplains are occupied by meandering and anastomosing streams that have deposited large tracts of sands and gravels (O'Connor and others, 2001). Smaller streams, such as the Pudding River, have not been able to down cut completely through the Willamette Silt in most areas of the valley lowland. Holocene sediments deposited by the smaller streams are generally restricted to silty sands, silts, or clays.

Hydrogeologic Units

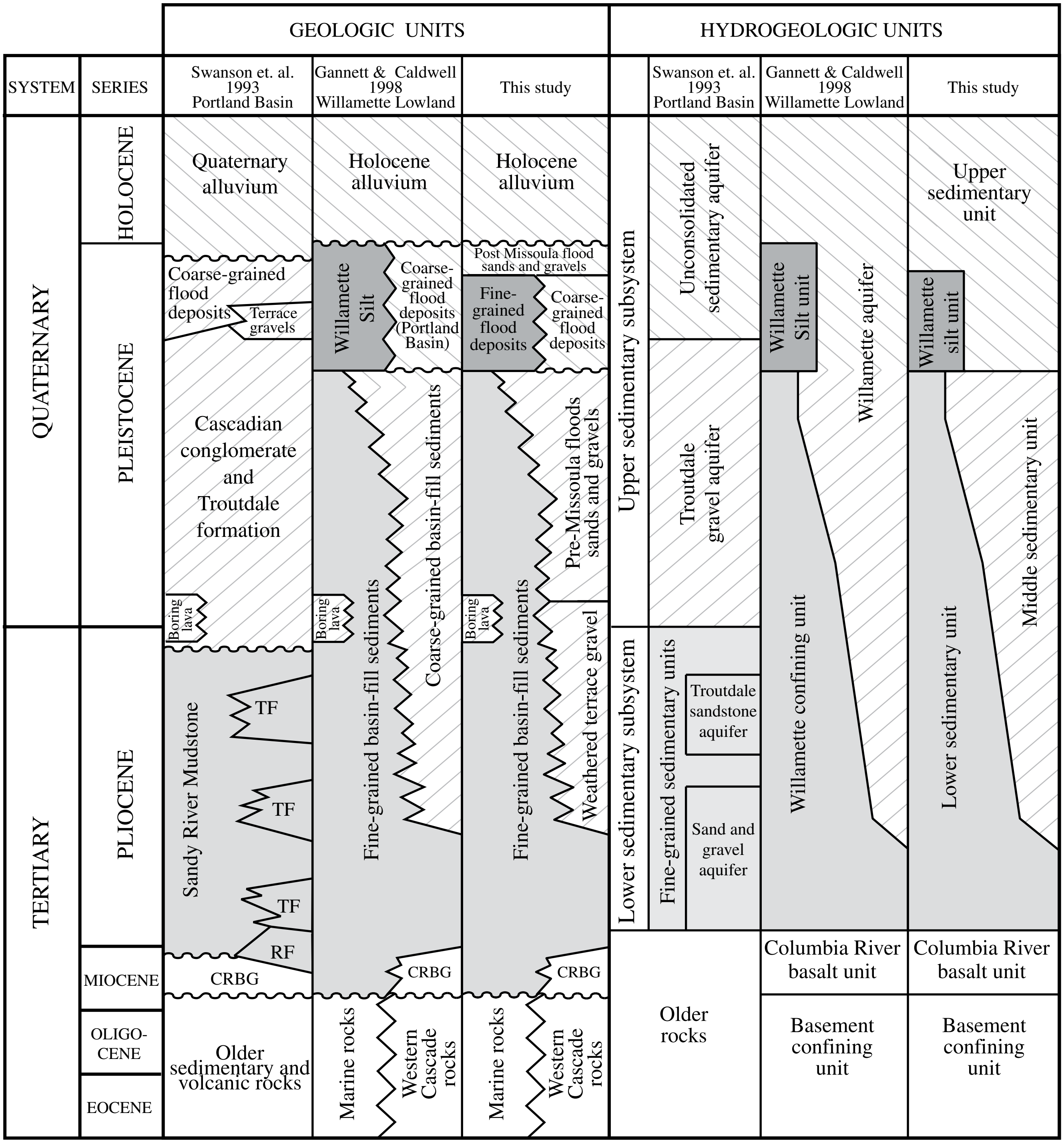
For the purposes of this study, seven regional hydrogeologic units, which consist of one or more geologic units with similar hydrogeologic properties at a regional scale, are defined in the Willamette Basin: (1) the High Cascade unit, (2) the upper sedimentary unit, (3) the Willamette silt unit, (4) the middle sedimentary unit, (5) the lower sedimentary unit, (6) the Columbia River basalt unit, and (7) the basement confining unit. This usage parallels that of Woodward and others (1998) with the addition of the High Cascade unit and the subdivision of their Willamette aquifer into a younger, more permeable upper and older less permeable middle sedimentary unit. Previous investigators (McFarland and Morgan, 1996; Piper, 1942; Price, 1967a; 1967b; Frank, 1973; Woodward and others, 1998) recognized that younger coarse-grained material had higher permeabilities than older coarse-grained material. Information from these studies and mapping by O'Connor and others (2001) allows a broad division of the coarse-grained basin-fill sediments into two regional hydrogeologic units based on permeability contrasts.

The Willamette silt unit and the upper, middle, and lower sedimentary units are unconsolidated, nonmarine, basin-fill sediments that generally post-date the Columbia River Basalt Group. The upper and middle sedimentary units correspond to the Willamette aquifer, and the lower sedimentary unit corresponds to the Willamette confining unit of Woodward and others (1998). Geologic and hydrogeologic units for this investigation and several earlier ground-water studies in the basin are correlated in figure 3. The High Cascade unit, which is only found in the eastern part of the study area, is not included in figure 3.

Descriptions of each hydrogeologic unit are presented in the following sections of this report. General unit descriptions are summarized from Swanson and others (1993), McFarland and Morgan (1996), Gannett and Caldwell (1998), and Woodward and others (1998), which provide the framework for the current study. The reader is referred to these reports for detailed unit descriptions. Additional information is provided where new data and analyses from the current study were used to modify unit characteristics. Most of the modifications were to the productive units: the upper and middle sedimentary units and the Columbia River basalt unit.

A map of the distribution of hydrogeologic units at land surface and cross sections of the distribution of the units in the subsurface are shown in plate 1. Thickness maps for basin-fill sediment units were prepared by modifying maps produced by Gannett and Caldwell (1998) using well data (Orzol and others, 2000) and geologic maps (O'Connor and others, 2001) compiled as part of this investigation.

Hydraulic properties were compiled for each hydrogeologic unit and summarized. Most historic data for aquifer tests are reported as transmissivity, a measure of an aquifer's ability



TF= Troutdale Formation
RF= Rhododendron Formation
CRBG= Columbia River Basalt Group

Hatches and shading show correlation between hydrogeologic and geologic units for this and previous studies

Figure 3. Correlation chart of hydrogeology, Willamette Basin, Oregon.

to transmit water that is equal to the product of the hydraulic conductivity and the saturated thickness of the aquifer. To facilitate a comparison of hydraulic properties, transmissivity values were converted to hydraulic conductivity by dividing the reported transmissivity by the open interval of the well, which yields a maximum value of hydraulic conductivity in most cases. The other aquifer property estimated from aquifer tests is the storage coefficient, which is defined as the volume of water released from storage per unit surface area of the aquifer per unit change in head.

High Cascade Unit

The High Cascade unit (HCU) consists of young, relatively unaltered volcanic material erupted from Pleistocene to Holocene-age volcanoes (Ingebritsen and others, 1994) along the crest of the Cascade Range. The unit is at land surface on the eastern edge of the study area (pl. 1) and is greater than 1,000 ft (feet) thick. The area underlain by the High Cascade unit is largely forest, barren areas of volcanic material, alpine meadows, and snowfields.

Permeability is high in the upper part of the High Cascade unit and decreases with depth (Ingebritsen and others, 1994; Manga, 1996; Hurwitz and others, 2003; Saar and Manga, 2003, 2004). Saar and Manga (2004) estimate that hydraulic conductivity ranges from 100 to 1,000 ft/d (table 1) in the upper 100 ft and decreases to 0.1 ft/d at depths around 1,000 ft. In a ground-water flow model of the Deschutes Basin, the upper 1,500 ft of material in the High Cascade area was simulated with a hydraulic conductivity of 6 to 20 ft/d (Gannett and Lite, 2004).

These studies suggest that precipitation and snowmelt easily infiltrate into the permeable High Cascade unit. Ground water follows shallow, short flow paths and contributes to the large discharge of cold springs within the High Cascades area. Ground water that follows deeper and longer flowpaths carries heat away from the volcanic arc and discharges as hot springs near the contact of the High Cascade unit and the basement confining unit. Although development of ground water is limited in the High Cascade area, high ground-water recharge and discharge rates of the unit are important in sustaining streamflow through the year in the major streams that drain the Cascade Range.

Upper Sedimentary Unit

The upper sedimentary unit (USU) consists primarily of unconsolidated sands and gravels of late Pleistocene and Holocene age, and is equivalent to the unconsolidated aquifer of McFarland and Morgan (1996) in the Portland Basin and the younger alluvial floodplain deposits (Piper, 1942; Price, 1967a, 1967b; Frank, 1973; Woodward and others, 1998) in the central and southern Willamette Basins. The unit is exposed at land surface throughout its extent. It is absent in the Tualatin Basin.

In the Portland Basin, the unit is largely composed of coarse-grained Missoula Flood deposits. The unit also includes the late Pleistocene and Holocene alluvium, and unconsolidated terrace deposits along major streams. The unit is approximately 50 ft thick in the central part and more than 150 ft thick in the western part of the Portland Basin (fig. 4).

In areas south of the Portland Basin, the upper sedimentary unit is generally equivalent to units mapped by O'Connor and others (2001) as post-Missoula Flood gravels and Holocene floodplain deposits. The post-Missoula Flood gravels represent the last pulse of Pleistocene alluvial fan deposition in the Willamette Valley. They occur as sand and gravel at land surface that form the upper surface of Pleistocene alluvial fans or as terraces inset along the upper reaches of major Cascade streams. The upper sedimentary unit includes Holocene floodplain deposits of the Willamette River and its major Cascade tributaries where channel gravels were deposited by meandering and anastomosing river systems. Near the Cascade Range, the floodplain deposits are inset into older alluvial fan surfaces. In the valley lowland, the upper sedimentary unit occurs in floodplains that occupy steep-walled trenches that have been incised through the entire thickness of the Willamette silt unit. The total thickness of these sediments is generally less than 40 ft, and the average thickness is about 20 ft (fig. 4).

The upper sedimentary unit is characterized by high permeability, high porosity, and high well yield. It is the most productive aquifer in the Willamette Basin, especially where it is dominated by thick sections of Missoula Flood gravels or Holocene floodplain gravels. Large diameter wells in the unit are capable of yielding up to 10,000 gal/min (gallons per minute) and commonly yield several thousand gallons per minute. Reported hydraulic conductivities range from 0.03 to 24,500 feet per day (ft/d) (table 1 and fig. 5). McFarland and Morgan (1996) estimate a median hydraulic conductivity in the Portland Basin of 220 ft/d. Data from Woodward and others (1998) indicate a mean conductivity of 600 ft/d in the areas south of the Portland Basin. Ground water in the unit is generally unconfined, and specific yields range from 0.003 to 0.2.

Willamette Silt Unit

The Willamette silt hydrogeologic unit (WSU) includes fine-grained deposits that occur at land surface in the lowland, except in the floodplains of the large streams, where the unit has been removed by erosion. The Willamette silt unit is underlain by the middle sedimentary unit in most places. The bulk of the unit is composed of deposits mapped as fine-grained Missoula Flood sediments by O'Connor and others (2001). These map units largely correspond to the Willamette Silt of Allison (1953) and Glenn (1965). The Willamette silt unit also includes minor amounts of other fine-grained deposits that are laterally or vertically contiguous with the Willamette Silt geologic unit.

The Willamette Silt contains as many as 40 planar beds of micaceous silt and clay that range from several inches to

Table 1. Hydraulic properties of hydrogeologic units in the Willamette Basin, Oregon.

[K_h, horizontal hydraulic conductivity in feet per day; K_v, vertical hydraulic conductivity in feet per day; S, storage coefficient; HCU, High Cascade unit; WSU, Willamette silt unit; USU, upper sedimentary unit; MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; BCU, basement confining unit; ft, feet]

Unit	K_h	K_v	S	Reference
HCU	10^{-4}–10^{-1}	--	--	Hurwitz and others, 2003, geothermal modeling
	10^{2}–10^{3}	--	--	Saar and Manga, 2004, seismicity and recharge
	10	--	--	Manga, 1996, spring discharge modeling
	10^{-3}–10^{-2}	--	--	Ingebritsen and others, 1994, geothermal modeling
USU	600	2.0	--	Woodward and others, 1998, model calibration, final estimate
	550–24,500	--	--	Woodward and others, 1998, specific capacity tests
	3–450; median = 140	--	--	Morgan and McFarland, 1996, model calibration
	0.03–7,000; median = 200	--	0.003–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests
	median = 170	--	0.2	Gonthier, 1983, specific capacity tests
WSU	0.03	0.0004	--	Iverson, 2002, model calibration
	0.2	0.008	--	Iverson, 2002, slug and permeameter tests
	1	0.01	--	Woodward and others, 1998, model calibration
	0.3–1.4	--	0.2–0.3	Wilson, 1997, core analysis
		0.04–0.7	--	Conlon and others, 2003, model calibration
	0.01–8		0.2–0.3	Price, 1967a, core analysis
MSU	6–31; mean = 202	--	0.0003–0.0005; 0.0002–0.003	See table 2, aquifer test
	0.002–0.008	--	--	Iverson, 2002, slug test
	6.8	6.8	--	Iverson, 2002, model sensitivity analysis
	200	2.0	--	Woodward and others, 1998, model calibration
	8–2,230	--	--	Woodward and others, 1998, specific capacity
	3–200; median = 16	--	--	Morgan and McFarland, 1996, model calibration
	0.03–1500; median = 7	--	0.0008–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests
LSU	200–220	--	0.0003	See table 2, aquifer test
	5	0.10	--	Woodward and others, 1998, model calibration
	160	--	0.07	Woodward and others, 1998, aquifer tests

Table 1. Hydraulic properties of hydrogeologic units in the Willamette Basin, Oregon—Continued.

[K_h, horizontal hydraulic conductivity in feet per day; K_v, vertical hydraulic conductivity in feet per day; S, storage coefficient; HCU, High Cascade unit; WSU, Willamette silt unit; USU, upper sedimentary unit; MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; BCU, basement confining unit; ft, feet]

Unit	K_h	K_v	S	Reference
LSU	0.8–32, median = 4	--	--	Wilson, 1997, core analysis
	1–150	--	--	Morgan and McFarland, 1996, model calibration
	0.02–200	--	0.00005–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests; higher values reflect Troutdale Sandstone aquifer and sand and gravel aquifer
	median = 19	--	0.001– 0.2	Gonthier, 1983, specific capacity tests
CRB	22–1,100	--	0.0004	See table 2, aquifer tests
	6	--	--	Woodward and others, 1998, aquifer tests
	2.5	0.03	--	Woodward and others, 1998, model calibration
	0.1–3; median = 2.5	--	--	Morgan and McFarland, 1996, model calibration
	<0.001–200; median = 0.3	--	0.0001–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests
	0.001–0.1	--	--	Woodward and others, 1998, structurally affected basalts
	1–3	--	--	Woodward and others, 1998, undeformed basalts
	0.001–750; median = 1	--	--	Woodward and others, 1998, CRB plateau
	10^{-7}–10^{3}			Reidel and others, 2002, core analysis of interflow zones (Pasco Basin, Washington)
	10^{-10}–10^{-4}; mean = 10^{-8}–10^{-7}	--	--	Reidel and others, 2002, core analysis of flow interiors (Pasco Basin, Washington)
	10^{-5}–10^{3}; 10^{-7}–10^{2}	--	--	Reidel and others, 2002, Wanapum and Grande Ronde basalt flow tops (Pasco Basin, Washington)
BCU	10^{-5}–10^{-2}	--	--	Ingebritsen and others, 1994, geothermal modeling
	0.2–0.3	--	0.00005–0.003	Gonthier, 1983, specific capacity tests

[1]Hydraulic conductivity calculated by dividing transmissivity by the open interval of well.

[2]Hydraulic conductivity calculated by dividing transmissivity by the thickness of the aquifer (220 ft) in the study area, rather than open interval (40 ft).

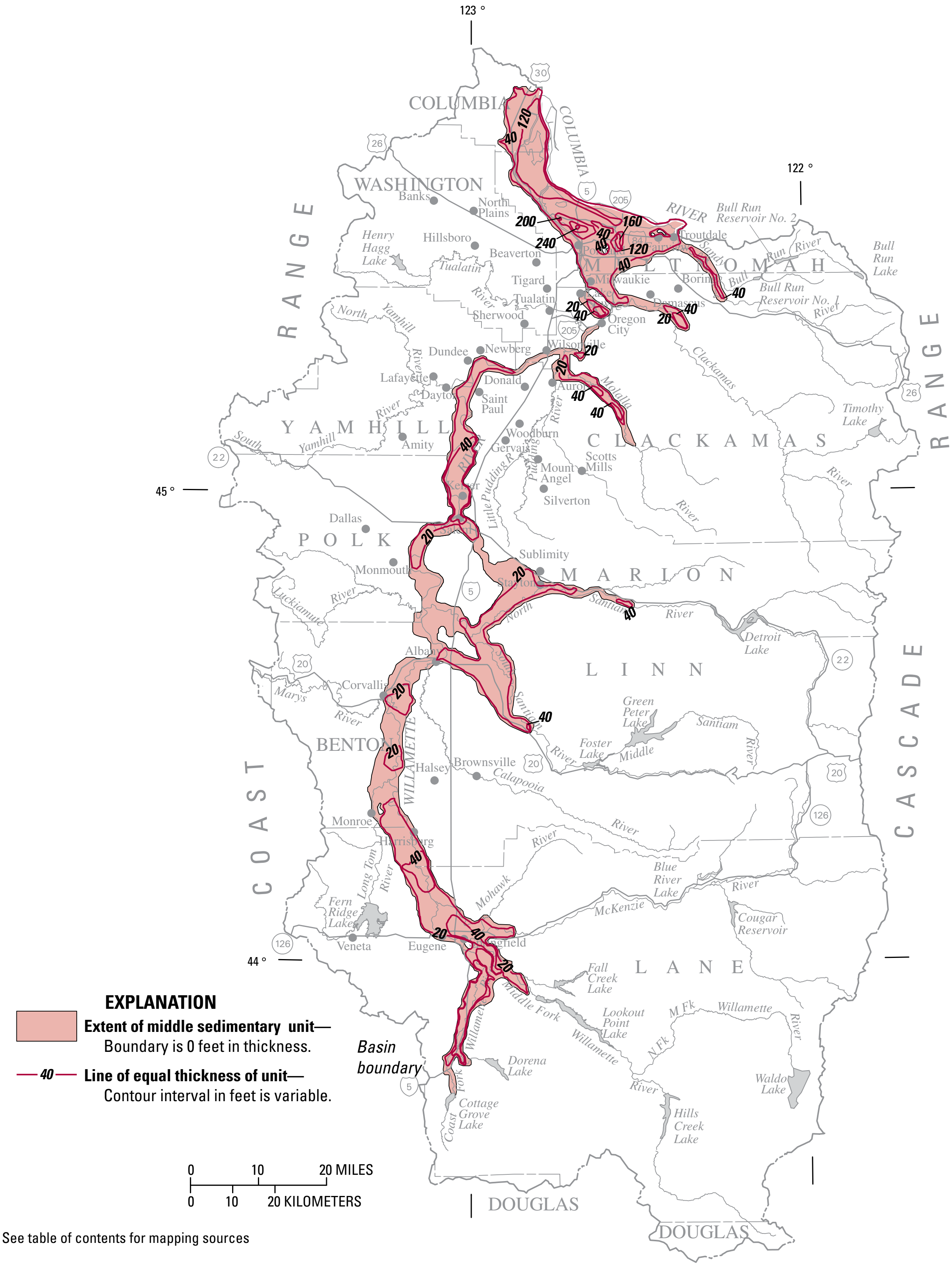


Figure 4. Extent and thickness of the upper sedimentary unit (modified from O'Connor and others, 2001).

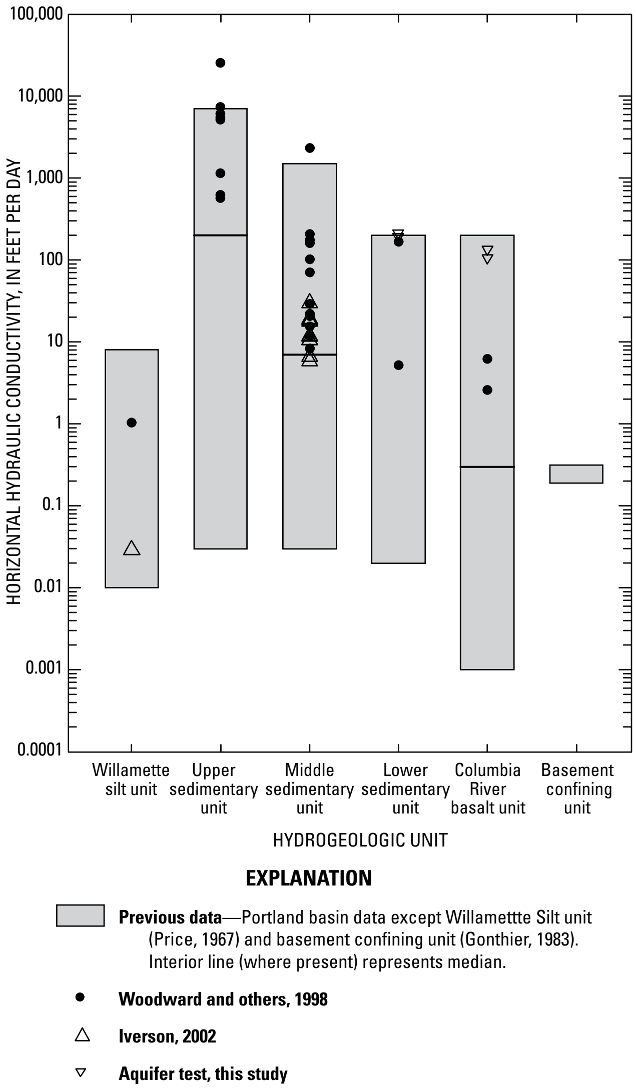


Figure 5. Hydraulic conductivity of hydrogelogic units, Willamette Basin, Oregon.

several feet thick. Many of the beds display a subtle internal grading that produces a rhythmic pattern of alternating bands of relatively coarse and fine-grained sediments. Although the majority of the unit consists of silt, clay can form a sizable fraction of the bulk sediment (Glenn, 1965). In the area southwest of Mount Angel, many of the lower beds are composed of plastic, silty blue clay (Iverson, 2002). These clayey beds are also exposed along the Pudding River near Mount Angel, where they commonly form resistant ledges in cut banks at stream level. Similar silty clay and clayey silt beds are common in the streambeds of many smaller streams, such as Case, Mill, and Champoeg Creeks, which are entrenched into the Willamette Silt in the central Willamette Basin between Salem and Wilsonville.

Although the Willamette Silt forms thick deposits in the Tualatin Basin, it cannot easily be distinguished on water-well logs from the fine-grained basin-fill deposits that underlie it. For this reason, it is not treated as a separate hydrogeologic unit in the Tualatin Basin but is lumped into the lower sedimentary unit.

The Willamette silt unit occurs at land surface throughout most of the Willamette lowland south of the Portland Basin below an elevation of 400 ft, except where it has been removed by erosion in the floodplains of the Willamette River and its main tributaries (pl. 1). In the central basin, the unit is greater than 60 ft thick and locally exceeds 120 ft in thickness (fig. 6). In the southern valley, the unit is generally less than 20 ft thick. The unit thins at the margins of the valley floor where it laps up against the highlands.

The Willamette silt unit generally has high porosity but low permeability. Although the unit is seldom exploited as an aquifer, sandy silts or silty, fine-grained sands that are capable of providing adequate water for domestic needs occur in some areas. Shallow pit wells in the silt were an important water supply for many early settlers in the Willamette Valley (Piper, 1942).

The regional water table generally occurs near land surface in the Willamette silt unit. Although the unit yields little water to wells because of its low permeability, the unit is capable of storing a considerable amount of ground water because of its high porosity. This stored ground water may be an important source of recharge to the underlying middle sedimentary unit.

In the central Willamette Basin, where the silt is thick, the underlying upper sedimentary unit behaves as a confined aquifer. In the southern Willamette Basin, where the silt is thinner, the underlying upper sedimentary unit behaves as an unconfined aquifer.

Because few wells are open to the Willamette silt unit, hydraulic properties based on well tests are lacking. In the central Willamette Basin, Price (1967a) reported hydraulic conductivities that range from 0.01 to 8 ft/d based on four core samples (table 1 and fig. 5). Iverson (2002) reports a horizontal hydraulic conductivity range of 0.2 ft/d based on slug tests and 0.003 ft/d from model calibration in the Mount Angel area. Wilson (1997) reports conductivities of 0.3 and 1.4 ft/d for two core samples of Willamette Silt in the Tualatin Basin. Although the Willamette Silt in the Tualatin Basin is included in the lower sedimentary unit in this report, these samples provide some constraints on the hydraulic properties of the Willamette silt unit in other areas. Core porosity measurements from the above sources indicate porosities ranging from 20 to 45 percent and specific yields of 0.2 to 0.3. All of these values are probably subject to large uncertainties because of the potential effects of sample disturbance during the coring and measurement processes.

Because the Willamette silt unit is widespread at land surface, the vertical hydraulic conductivity of the unit controls infiltration of recharge into the silt, recharge to underlying aquifers, and the exchange of ground water between underlying aquifers and streams underlain by the silt unit. Iverson (2002) reports an average vertical hydraulic conductivity of approximately 0.008 ft/d based on shallow core measurements. Most other reported estimates are derived indirectly from mod-

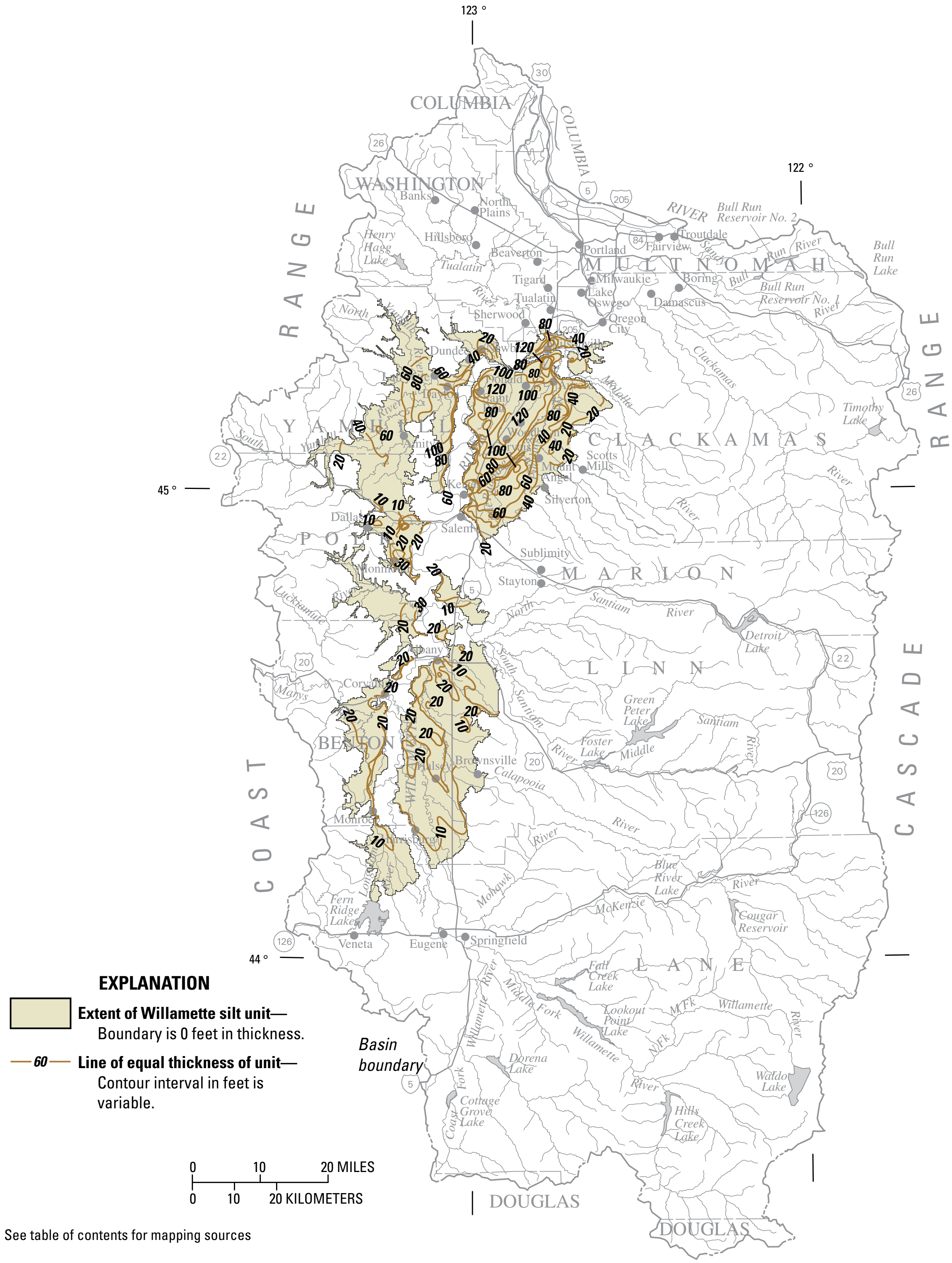


Figure 6. Extent and thickness of Willamette silt unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

els. Conlon and others (2003) obtained values of 0.04 to 0.7 ft/d by simulating heat transport beneath streams in the central Willamette Basin, which probably represent maximum values because the models assume only one-dimensional vertical flow of ground water. Vertical hydraulic conductivity values of 0.01 ft/d (Woodward and others, 1998) and 0.00004 ft/d (Iverson, 2002) were used in numerical ground-water flow models.

Middle Sedimentary Unit

The middle sedimentary unit (MSU) consists mainly of slightly to moderately consolidated Pleistocene sands and gravels that predate the Missoula Floods. The unit overlies the predominantly fine-grained lower sedimentary unit and is generally overlain by the younger sands and gravels of the upper sedimentary unit or the fine-grained Willamette silt unit (pl. 1).

In the Portland Basin, the middle sedimentary unit is equivalent to the Troutdale gravel aquifer of McFarland and Morgan (1996), which largely consists of consolidated gravels of the upper Troutdale Formation and younger volcaniclastic conglomerates derived from the Cascade Range of Pliocene to early Pleistocene age. It also includes basaltic lavas, vent plugs, and volcanic debris of the Boring Lavas, which are the products of Pliocene to Pleistocene volcanoes that erupted within the Portland Basin. The Boring Lavas and interbedded sediments form the highlands east of Oregon City that separate the Portland Basin from the central Willamette Basin. The middle sedimentary unit is generally 300 to 400 ft thick in the Portland Basin but locally exceeds a thickness of 500 ft (fig. 7).

Outside of the Portland Basin, the middle sedimentary unit includes units mapped by O'Connor and others (2001) as the Troutdale Formation, weathered terrace gravels, and pre-Missoula Flood sands and gravels. The Troutdale Formation and the weathered terrace gravels consist of Pliocene to Pleistocene fluvial gravels that generally occur as isolated terraces and alluvial fan remnants at higher elevations on the margins of the valley floor. The pre-Missoula Flood sands and gravels are late Pleistocene alluvial fan and braid-plain deposits that flank the eastern and southern margin of the valley.

The alluvial fan and braid-plain gravels form the bulk of the middle sedimentary unit in the central Willamette Basin and the southern Willamette Basin. The unit thickens where alluvial fans occur along the eastern and southern margins of the valley associated with the Willamette, McKenzie, South Santiam, North Santiam, and Molalla Rivers (fig. 7). Thickness exceeds 150 ft in most of the alluvial fans and is in excess of 200 ft in the larger fans associated with the Willamette, McKenzie, and North Santiam Rivers. On the broad valley floor beyond and between the alluvial fans, the unit is generally less than 60 ft thick. The middle sedimentary unit is commonly unconsolidated near its upper surface but typically becomes more compacted and cemented with depth. On drillers' logs it is typically described as cemented sand and gravel or conglomerate. In quarry exposures, the middle sedimentary unit commonly shows steep vertical faces, especially in the deeper portions of the unit.

Reported hydraulic conductivities for the middle sedimentary unit (table 1 and fig. 5) in the Portland Basin range from 0.03 to 1,500 ft/d (McFarland and Morgan, 1996). Reported conductivities south of the Portland Basin for buried alluvial fan deposits range from 8 to 2,230 ft/d (Woodward and Gannett, 1998; Iverson, 2002).

Storage coefficients for the unit range from 0.0002 to 0.2 (table 1). In the central Willamette Basin, where the middle sedimentary unit is generally overlain by more than 40 ft of saturated Willamette Silt, the unit is confined and storage coefficients are probably less than 0.001. In the southern Willamette Basin, where the unit is typically overlain by less than 20 ft of saturated Willamette Silt and in the Portland Basin where the unit occurs at land surface, the unit is unconfined to semiconfined, and storage coefficients are probably greater than 0.001.

Lower Sedimentary Unit

The lower sedimentary unit (LSU) corresponds to the Willamette confining unit of Gannett and Caldwell (1998) and the lower sedimentary subsystem of Swanson and others (1993) in the Portland Basin (fig. 3). The unit overlies the basement confining unit or the Columbia River basalt unit and is overlain by the middle sedimentary unit or the Willamette silt unit (pl. 1). The lower sedimentary unit constitutes the bulk of the basin-fill sediments in the Willamette Basin.

In the Portland Basin, the lower sedimentary unit includes the Sandy River Mudstone and sands and gravels that are part of the Troutdale Formation (McFarland and Morgan, 1996). The maximum thickness is approximately 1,200 ft in the center of the basin (fig. 8). Fine-grained deposits of the Sandy River Mudstone dominate the unit in the western two-thirds of the basin but are interbedded with coarse-grained Columbia River channel deposits and vitric sandstones of the Troutdale Formation in the east. In these areas, McFarland and Morgan (1996) locally subdivided the unit into the sand and gravel aquifer, the Troutdale sandstone aquifer, and several confining units.

Outside of the Portland Basin, the lower sedimentary unit consists of predominantly fine-grained sediments that include distal alluvial fan deposits, low-energy stream sediments, and lacustrine deposits. On well logs, the unit is commonly described as blue clay with minor interbeds of sand and gravel.

In the Tualatin Basin, the lower sedimentary unit includes the predominantly fine-grained Hillsboro Formation (Wilson, 1997) and the overlying Willamette Silt, which have an aggregate maximum thickness of about 1,400 ft (fig. 8). These geologic units are combined into a single hydrogeologic unit because they are not readily distinguished on the basis of well logs and have similar hydrologic properties at the regional scale. Discontinuous beds of silty sand with minor gravel, deposited by low-gradient meandering streams, are common

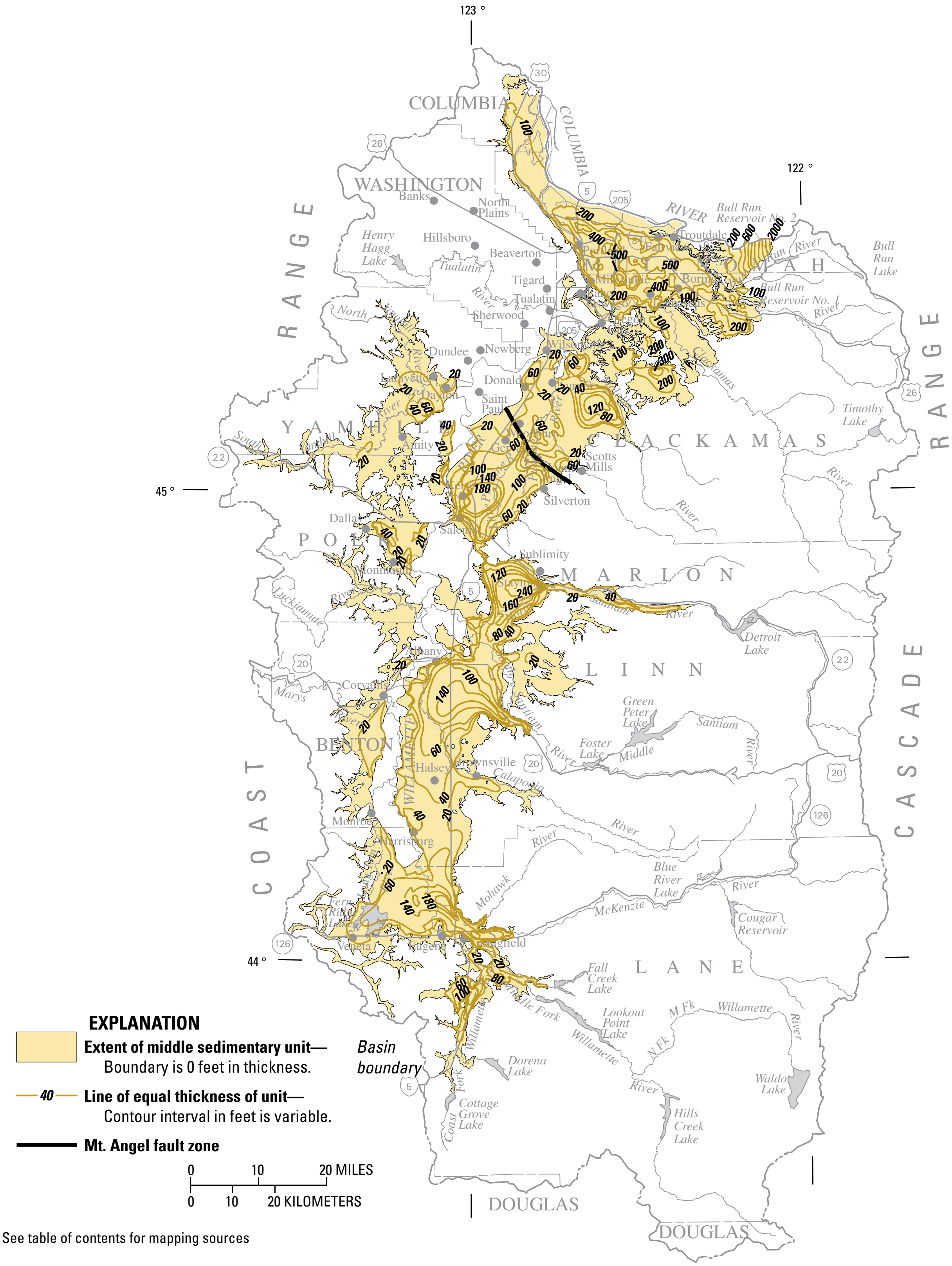


Figure 7. Extent and thickness of the middle sedimentary unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

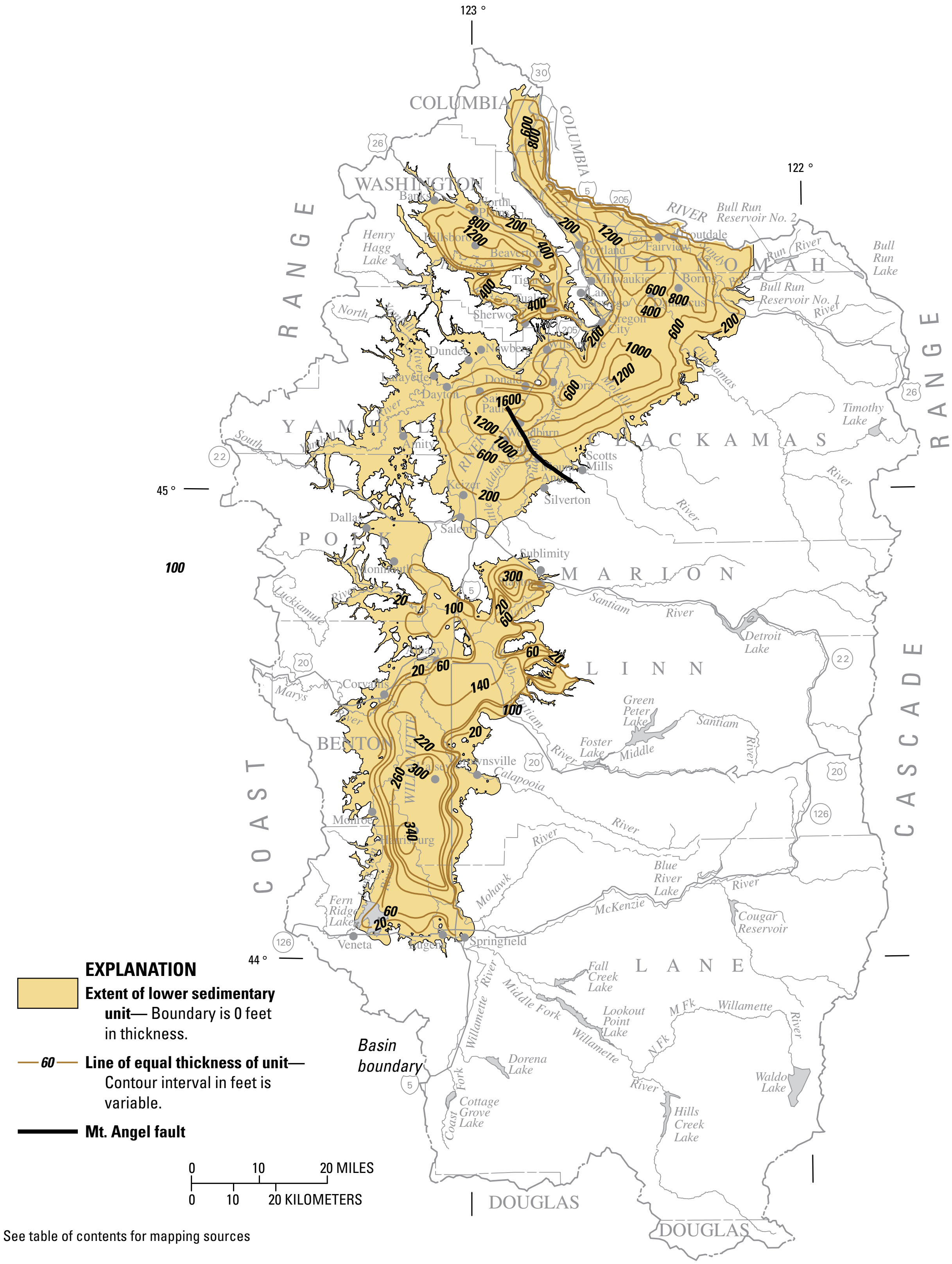


Figure 8. Extent and thickness of the lower sedimentary unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

in the upper part of the Hillsboro Formation but become less common with depth (Wilson, 1997).

In the central and southern Willamette Basins, the lower sedimentary unit consists mostly of distal alluvial fan sediments deposited by Cascade Range streams and fine-grained sediments deposited by Coast Range streams. The boundary between the lower sedimentary unit and the sands and gravels of the middle sedimentary unit generally corresponds to a facies boundary between proximal and distal portions of Pleistocene alluvial fans that developed on the eastern and southern margins of valley (Gannett and Caldwell, 1998). Consequently, these unit boundaries are approximate because the change between the predominantly coarse-grained (middle sedimentary unit) and the predominantly fine-grained (lower sedimentary unit) portions of the fans is gradational. In places, near these unit boundaries, the lower sedimentary unit contains considerable proportions of sand and gravel. Also, in some areas, thin sand and gravel beds extend into distal portions of the basin that are included in the lower sedimentary unit.

On a regional scale, the lower sedimentary unit can be characterized as a confining unit. Locally, however, the unit has productive sand and gravel beds or a cumulative thickness of thin sands that are sufficient to allow moderate to high well yields. In the Portland Basin, the production capacity of the coarse-grained deposits in the unit is considerably higher than in most other areas, and large diameter wells can yield up to 3,000 gal/min (McFarland and Morgan, 1996). In the Tualatin Basin, wells that intersect multiple sand beds can yield up to 100 gal/min, but more commonly wells yield less than 10 gal/min (Wilson, 1997). In the central Willamette Basin, wells open to discontinuous sands and gravels in the upper part of the unit are capable of yielding moderate to high quantities of water, especially if they have large open intervals and gravel-pack completions. For example, many irrigation wells between Woodburn and Newberg produce up to 250 gal/min from the lower sedimentary unit and some are capable of producing 1,000 gal/min. Elsewhere in the central Willamette Basin and southern Willamette Basin, sand beds are less common in the lower sedimentary unit and well yields are typically less than 20 gal/min.

Reported hydraulic conductivities for the lower sedimentary unit (table 1 and fig. 5) range from 0.02 to 200 ft/d in the Portland Basin (McFarland and Morgan, 1996). Conductivities of sand beds in the Tualatin Basin range from 0.8 to 32 ft/d (Wilson, 1997). Aquifer tests in the central Willamette Basin indicate conductivities as high as 220 ft/d (table 2). However, since most wells are open to the coarse-grained component of the lower sedimentary unit, the bulk conductivity is probably lower than the reported values in most places. Reported storage coefficients for the unit range from 0.00005 to 0.2 (tables 1 and 2). Since the unit is confined throughout most of its extent, storage coefficients less than 0.001 are assumed to be representative for the unit.

Columbia River Basalt Unit

The Columbia River basalt unit (CRB) consists of a series of flood-basalt lavas of the Miocene Columbia River Basalt Group, which is divided into the Imnaha Basalt, Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt formations (Tolan and others, 1989). Only flows of the Grande Ronde and Wanapum Basalt are present in the Willamette Basin. Wanapum flows are present in the Portland Basin and on the margins of the central Willamette Basin but are absent in the Tualatin Basin (Beeson and others, 1989a). More than 50 flows are present in the Portland area, but less than a dozen occur in the Salem area (Beeson and others, 1989a; Tolan and others, 1999, 2000a). Individual basalt flows in the Willamette Basin typically range from 40 to 100 ft thick, but flow thickness is highly variable and may exceed 250 ft in some areas (Beeson and others, 1989a; Tolan and others, 1999, 2000a). Thick flows are common at the base of the Columbia River basalt unit and in paleoriver canyons of the ancestral Columbia River. The unit is underlain by the basement confining unit, generally overlain by the lower sedimentary unit, and locally overlain by the upper and middle sedimentary unit in the lowland. East of the Portland and central Willamette Basins, the unit is both underlain and overlain by volcanic deposits of the basement confining unit.

The extent and altitude of the upper surface of the Columbia River basalt unit (fig. 9) is based on work by Gannett and Caldwell (1998) with modifications from regional scale maps (Tolan and others, 1989; Beeson and others, 1989a), geologic maps (Beeson and others, 1989b, 1991; Broderson, 1994; Madin, 1994; Tolan and others, 1999, 2000a), and well data. The thickness of the unit (fig. 10) is constrained by lithologic descriptions of 600 field located wells (76 of which fully penetrate the unit), measured sections in outcrop areas (Anderson, 1978; Vogt, 1981), published geologic maps, and structural features (Beeson and others, 1989a; Gannett and Caldwell, 1998) that controlled the thickness and distribution of flows. Because of limited well control, the altitude of the upper surface and thickness of the basalt is highly uncertain in many areas.

Contours of the top of the Columbia River basalt unit (fig. 9) show a planar upper surface that dips at low angles (generally less than 10 degrees) toward the centers of structural basins in the northern Willamette lowland. In general, this surface appears to correspond to a dip slope at the top of the uppermost basalt flows with some modification by erosion. Changes in the altitude of the top of the Columbia River basalt unit of more than 400 ft are inferred across the Gales Creek-Mount Angel structural zone (fig. 9) based on well data (Gannett and Caldwell, 1998). The altitude of the upper surface of the basalt is about -1,600 ft in the center of the Portland Basin, -1,200 ft in the center of the Tualatin Basin, -1,600 ft in the center of the central Willamette Basin, and -200 ft in the center of the Stayton Basin.

The total thickness of the Columbia River basalt unit (fig. 10) is greatest east of Portland, where it is more than 2,000 ft thick. Elsewhere in the study area, the unit generally ranges

Table 2. Summary of selected aquifer tests in the Willamette Basin, Oregon.

[OWRD well no., Oregon Water Resources Department well number; gpm, gallons per minute; Analysis method: SC, Theis solution using specific-capacity data (Lohman, 1979); T, Theis non-equilibrium curve matching; SL, straight-line method. Test conducted by: S, study team; C, private consultant. MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; ft^2/d, square feet per day; mi, miles; ft, feet; ft/d, feet per day; --, value not determined; ft, feet]

Basin	OWRD well no.	Well location and name	Discharge (gpm)	Duration (hours)	Drawdown (ft)	Distance from pumped well (ft)	Analysis method	Test conducted by	Transmissivity (ft^2/d)	Storage coefficient	Radius of influence (mi)	Open interval length (ft)	Hydraulic conductivity[6] (ft/d)	Unit
Portland	CLAC 4396	02S/02E-29DD Clackamas River Water—Well No. 1	300	24	2.9	0	SC	C[1]	22,000	--	0.7 - 0.9	258	85	CRB
Tualatin	WASH 8988	01S/01W-21CDD2 Tualatin Valley Water District—Hanson Rd	880	24	7.2	2,400	SL, T	C[2]	65,500	$4x10^{-4}$		630	100	CRB
Tualatin	WASH 8862	01S/01W-17CDB Tualatin Valley Water District—Schuepbach	770	10	39.9	0	SL, T	C[2]	6,820	--		305	22	CRB
Central	MARI 19624	08S/03W-10DC City of Salem—Woodmansee Park—ASR Well No. 1	1,000	24	5	45–465	SL, T	C[3]	32,000–38,000	$1x10^{-3}$–$1x10^{-4}$	4.8–8.0	36	890–1100	CRB
Central	MARI 50456	06S/01W-09DCA Mount Angel City Well No. 6	950	120	1.4–3.9	11,000–9,000	SL, T	S[4]	18,000–23,000	$2x10^{-4}$		160	110–140	CRB
Central	MARI 53920	06S/01W-08DAD01 Eder Irrigation Well	180	72	0.7–4.9	435–4,560	SL, T	C[5]	1,380–7,050	$2x10^{-4}$–$3x10^{-4}$		40	6–31	MSU
Central	MARI 18414	05S/02W-08CBC01 Kirsch Irrigation Well	750	120	4.39	2,578	T	S[4]	5,900–6,600	$3x10^{-4}$		30	200–220	LSU

Sources for tests:

[1] Golder Associates, 2000.

[2] CH2M Hill, 1997.

[3] Golder Associates, 1996.

[4] Oregon Water Resources Department, this study.

[5] Justin Iverson, 2002, Master's thesis, Investigation of the hydraulic, physical, and chemical buffering capacity of Missoula Flood deposits for water quality and supply in the Willamette Valley of Oregon.

[6] Iverson values calculated using aquifer thickness equal to 220 ft.

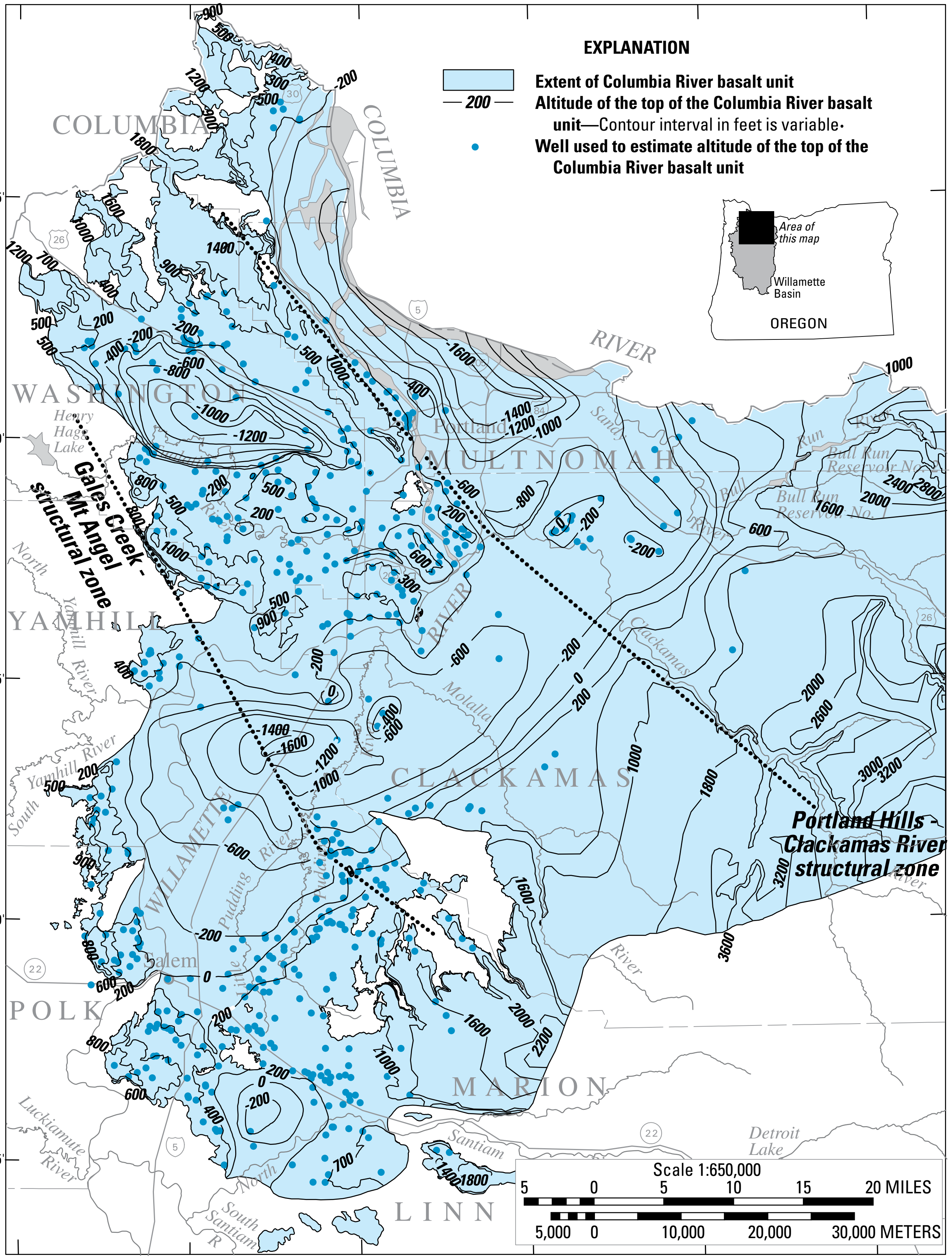


Figure 9. Extent and altitude of the top of the Columbia River basalt unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

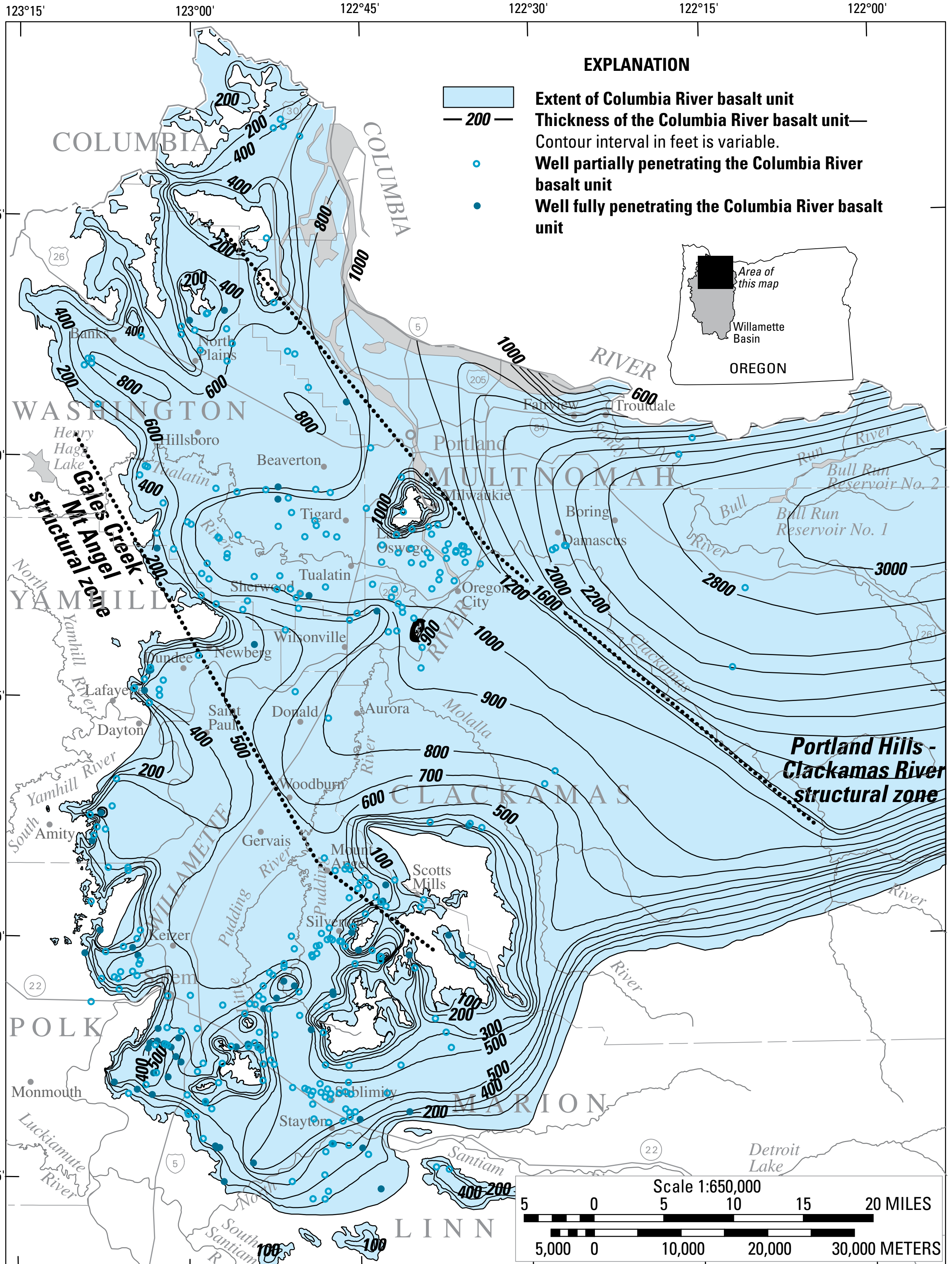


Figure 10. Extent and thickness of the Columbia River basalt unit, Willamette Basin, Oregon.

from 200 to 1,000 ft in thickness. Changes in the thickness of the Columbia River basalt unit are inferred across the Portland Hills-Clackamas River and Gales Creek-Mount Angel structural zones which created topographic barriers to southern movement of many flows (Beeson and others 1989a). Limited well data indicate a thick accumulation of Columbia River basalt lavas in the southern Tualatin Basin along the trend of the Chehelam Mountains (Beeson and others, 1989a). The structure contour and thickness maps show the general geometry of the Columbia River basalt unit on a regional scale. Local variations from faulting and stream incision in outcrop and subsurface areas are not shown on the maps.

The upper surface of the Columbia River basalt unit is commonly weathered to a red, lateritic clay that was produced during prolonged exposure at land surface after the emplacement of the uppermost basalt flow. The thickness of this weathered zone ranges from several ft in the Waldo Hills (Hampton, 1972) to more than 200 ft in the Tualatin Basin (Hart and Newcomb, 1965).

The Columbia River basalt unit is characterized by thin, often permeable, interflow zones separated by thick, low permeability flow interiors. Interflow zones include the top of one flow, the base of an overlying flow, and intervening sediments. Permeability and porosity are enhanced in interflow zones where the basalt surface was vesiculated or brecciated during emplacement. Thicker basal zones of brecciation occur where the basalt flowed over wet soils or standing water. Permeable interflow zones vary considerably in thickness and extent. The uppermost water-bearing zone in a stack of flows is unconfined but lower aquifers are confined.

Because the basalt lavas were generally emplaced as sheet flows, water-bearing zones occur in subhorizontal, tabular interflow zones separated by low-permeability flow interiors that act as confining beds. Permeable interflow zones probably comprise less than 10 percent of the total flow thickness and the porosity of these zones is probably less than 25 percent. Therefore, bulk porosity of the Columbia River basalt unit probably averages less than 3 percent and perhaps as little as 1 percent.

Well yields in the Columbia River basalt unit are moderate to high. Most high-capacity wells are open to multiple interflow zones. Large-diameter irrigation and public-supply wells commonly produce more than 250 gal/min (gallons per minute) and some are capable of 1,000 gal/min; smaller diameter domestic wells are generally capable of producing 20 gal/min. Production rates can be considerably less in areas with few interflow zones or interflow zones that lack permeability from vesiculation and brecciation.

Hydraulic properties in the basalt unit are a function of the permeability, thickness and number of interflow zones. Most reported values for hydraulic properties should be treated with caution because they depend on the assumption that ground-water conditions in the basalt are equivalent to conditions in a porous medium, such as sand and gravel. Reported hydraulic conductivity for the Columbia River basalt unit in the Willamette Basin ranges from 10^{-3} to 10^{3} ft/d (table 1 and fig. 5). Hydraulic conductivity values based on aquifer well tests are 22 and 100 ft/d in the Tualatin Basin, approximately 130 ft/d near Mount Angel, and 1,000 ft/d for brecciated basalt near Salem (table 2 and see aquifer test section). Reported storage coefficients range from 0.0001 to 0.2 (table 1 and 2).

Information about the permeability of interflow zones and flow interiors in the Columbia River basalt unit is available in the Pasco Basin of eastern Washington, where similar sheet flows of Columbia River basalt lava occur. Extensive testing of cores from these basalt lavas (Reidel and others, 2002) indicate horizontal hydraulic conductivities of 10^{-7} to 10^{3} ft/d (table 1) for individual interflow zones and a decrease with depth due to compaction and secondary mineral formation. The geometric mean hydraulic conductivity is 1 ft/d for shallow and 0.01 ft/d for deep interflow zones. Tests on cores from flow interiors indicate hydraulic conductivity ranges from 10^{-10} to 10^{-4} ft/d with a mean value between 10^{-8} and 10^{-7} ft/d (Reidel and others, 2002). Although flow interiors contain a dense network of hackly and columnar cooling joints, the joints are generally filled with secondary minerals, primarily clays (Tolan and others, 2000b; Reidel and others, 2002), which greatly reduce the permeability.

Saline water is common in deeper parts of the Columbia River basalt unit and is probably derived from connate water entrapped in the underlying marine sediments of the basin confining unit (Woodward and others, 1998). Upward flow of saline water may occur naturally along deep fault zones or be induced by pumping in deep basalt wells. Fluid conductivity, which is an indication of fluid salinity, shows the effect of saline water from the marine rocks on water quality in a well (02S/01W-32ADD) open to the Columbia River basalt unit (fig. 11 and pl. 1). The increase in fluid conductivity where the well terminates at the top of the underlying marine rocks of the basement confining unit suggests that the source of salinity is in the marine rocks. The upward flow or diffusion of the saline water affects water quality in the borehole open to the Columbia River basalt unit.

Ground-water pumpage from the unit may have induced the upward flow of deep saline water, causing salinities in the Columbia River basalt unit to increase over time in two irrigation wells in section 26, Township 1S, Range 1W between 1969 and 1996 (OWRD, unpub. data). In the Willamette Basin, the extent of salinity problems in the basalt is not known with certainty because the occurrence of saline water is generally not reported on well reports. Known occurrences are widely scattered throughout the basin and are usually associated with areas underlain by marine rocks.

Basement Confining Unit

The basement confining unit (BCU) includes Tertiary marine sedimentary rocks and Eocene volcanic rocks of the Coast Range, and volcanic and volcaniclastic rocks of the Western Cascade area (Gannett and Caldwell, 1998). The unit is exposed in the Coast Range and Western Cascade area and forms the floor of the Willamette Basin beneath all other

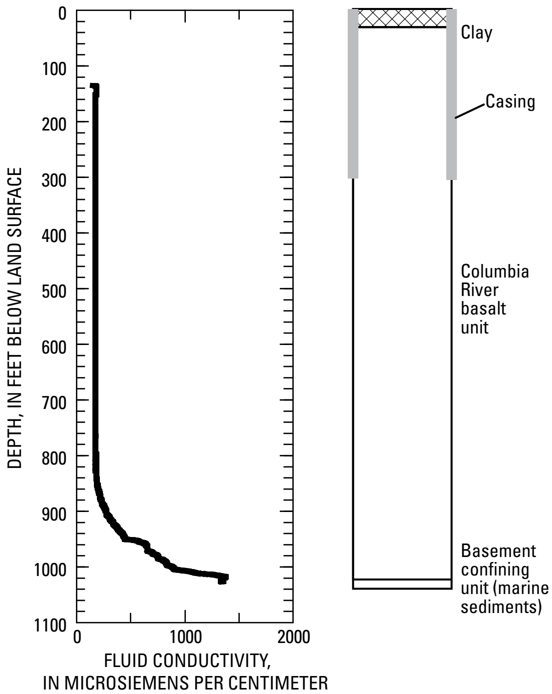


Figure 11. Fluid conductivity of a well (02S/01W-32ADD) open to the Columbia River basalt and basement confining units, Willamette Basin, Oregon.

hydrogeologic units (pl. 1). In areas east of the Portland and central Willamette Basins, volcanic material of the basement confining unit underlies and overlies the Columbia River basalt unit.

The basement confining unit includes a variety of geologic formations and rock types with widely varying properties. Caldwell (1993) provides a detailed description of the hydrogeologic characteristics of the rocks and sediments of the Coast Range near Salem. In general, the unit is composed of rocks in which most of the primary porosity has been destroyed by secondary mineralization.

The basement confining unit is characterized by low permeability, low porosity, and low well yield. Well yields are commonly less than 5 gal/min, and the unit is generally able to provide sufficient water for domestic uses only. Fracture porosity locally produces higher well yields. Individual fractures can have high permeability but the permeability of the matrix material is typically very low. Estimates of hydraulic conductivity (table 1 and fig. 5) of the basement confining unit range from 10^{-5} to 10^{-2} ft/d in the Western Cascade area using geothermal models (Ingebritsen and others, 1994) to 0.2 to 0.3 ft/d near the Coast Range in Polk County using specific capacity tests (Gonthier, 1983). The storage coefficient ranges from 0.00005 to 0.003 (Gonthier, 1983).

High salinity in ground water is common in the Tertiary marine sedimentary rocks of the basement unit (Piper, 1942; Caldwell, 1993; Woodward and others, 1998). Saline water in the unit originated as seawater that was trapped in the pore spaces of buried sediments (Woodward and others, 1998) and is common at depths greater than 100 ft (Piper, 1942). Because of the low porosity and permeability of the unit, fresh water is unable to circulate deep into the rocks to flush out saline waters.

Arsenic is a common natural constituent in ground waters of the basement confining unit, especially in areas underlain by silicic volcanic bedrock in Lane and south-central Linn Counties (fig. 1). Concentrations above the current Environmental Protection Agency (EPA) drinking water standard of 10 micrograms per liter (µg/L; about 10 parts per billion) are common, and concentrations above 500 µg/L have been observed (Hinkle and Polette, 1999).

Aquifer Tests

Aquifer tests were conducted as part of this study and compiled from reports submitted to OWRD from private consulting firms (table 2). The discussion below describes three constant-rate aquifer tests that were conducted in the central Willamette Basin during this study to better define the hydraulic properties of units in the area. A test in the middle sedimentary unit was conducted in cooperation with Oregon State University (Iverson, 2002). Two additional tests were conducted by the OWRD: one in the lower sedimentary unit and a second in the Columbia River basalt unit. For each test, a range in transmissivity is reported in table 2 that corresponds to the analysis of the response in multiple observation wells. In the description of each test, a single rounded value is reported.

An aquifer test of the middle sedimentary unit was conducted by Iverson (2002) using an irrigation well (06S/01W-08DAD01, pl. 1) near Mount Angel. A pumping rate of about 180 gal/min was maintained over a period of 3 days. In the vicinity of the well, about 220 ft of the middle sedimentary unit is overlain by about 60 ft of the Willamette silt unit. The pumped well is screened over a 40-foot interval of sand and gravel at the top of the middle sedimentary unit. Analysis of test results indicates an average transmissivity of 4,500 ft^2/d and a storage coefficient of about 0.0003 (Iverson, 2002). Assuming a unit thickness of 220 ft and neglecting any impacts of partial penetration, average hydraulic conductivity is 20 ft/d (table 2).

An aquifer test of the lower sedimentary unit was conducted using an irrigation well (05S/02W-08CBC01, pl. 1) located several miles south of St. Paul. Pumping was maintained at 750 gal/min over a 2-day period. The well is open over a 30-foot interval of sand beds in the upper part of the lower sedimentary unit. The completion interval is overlain by 70 ft of lower sedimentary unit clay, 30 ft of upper sedimentary unit sands, and 100 ft of the Willamette silt unit. Analysis of test results indicates a transmissivity of approximately 6,000 ft^2/d and a storage coefficient of 0.0003. Hydraulic conductivity is estimated to be 200 ft/d.

A 5-day aquifer test of the Columbia River basalt unit was conducted using a municipal well (06S/01W-09DCA) south of Mount Angel that was pumped at a rate of 950 gal/min. The well is open over an interval of 160 ft in the upper part of the basalt unit. The completion interval is overlain by 450 ft of fine-gained lower sedimentary unit, 190 ft of upper sedimentary unit sands and gravels, and 30 ft of Willamette silt unit. Analysis of the drawdown in observation wells assuming a porous medium indicates a transmissivity of 20,000 ft^2/d and a storage coefficient of 0.0002. A bulk hydraulic conductivity of about 125 ft/d is estimated by dividing the transmissivity by the completion interval of 160 ft. However, the hydraulic conductivity of the permeable interflow zones is likely to be considerably higher since interflow zones probably constitute a small fraction of the completed interval. The effective thickness of these zones in the pumped well could not be determined based on lithologic descriptions on the well log. If only 25 percent of the completion interval consists of permeable interflow zones, the effective permeability of the interflow zones would be 500 ft/d. If only 10 percent is permeable, the effective permeability would be 1,250 ft/d. Test results indicate that the Mount Angel fault zone acts as a barrier to ground-water flow in the vicinity of the city of Mount Angel over the time scale of the test. Observation wells south of the fault zone were affected by pumping from the test well but impacts were not seen north of the fault zone in wells at similar distances from the pumped well.

Hydrologic Budget

The processes that affect ground-water supply in the Willamette Basin include recharge by infiltration of precipitation and applied irrigation water, the exchange of water between surface- and ground-water systems, and discharge by evapotranspiration and wells. Each of these processes is discussed below in an attempt to quantify the amount of ground water entering and leaving the ground-water system.

Recharge from Precipitation and Applied Irrigation Water

Infiltration of precipitation into the ground-water system is the main source of recharge in the Willamette Basin. Locally, recharge also occurs by infiltration of irrigation water, stormwater through subsurface gravel galleries (drywells), and surface water. This section discusses recharge from these sources, except from streams, which is discussed in a separate section on surface- and ground-water interactions.

In previous studies, recharge was estimated in the Portland Basin using a water-balance model, referred to as the Deep Percolation Model or DPM (Bauer and Vaccaro, 1987), which incorporated infiltration of runoff from drywells and onsite waste disposal (Snyder and others, 1994), and in the Willamette lowland using estimates from previous reports, the DPM, and correlation between the percent of precipitation recharged and surficial geology (Woodward and others, 1998). Neither of these studies provides a rigorous, consistent estimate of recharge over the entire Willamette Basin.

For this study, recharge estimates were based on watershed modeling using the Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983), except in the Portland Basin, where recharge was based on estimates by Snyder and others (1994). The PRMS models simulated surface-water conditions on a daily basis and average annual recharge values were estimated for the 1995 and 1996 water years, a wetter than average period that corresponds to the period when synoptic water levels and annual water-use information were collected in the basin. Monthly recharge in the central Willamette Basin was simulated for the 1999 and 2000 water years, a period of average precipitation when continuous water levels and monthly water-use information were collected. PRMS was modified to incorporate infiltration of irrigation water. Details of the application of PRMS models in the Willamette Basin may be found in Lee and Risley (2002). The following discussion focuses on the area simulated by the watershed models, which includes the drainage area upstream of Portland.

The simulated average annual recharge for the 1995-96 period (fig. 12) in the Willamette Basin closely corresponds to observed precipitation patterns (fig. 2). Recharge ranged from 7 in/yr (inches per year) in the lowland areas, where precipitation is less than 55 in/yr, to more than 40 in/yr in areas in the Coast and Cascade Ranges, where precipitation is more than 100 in/yr. The average recharge for the basin for the period was 22 in/yr. For comparison, this rate of recharge is equivalent to 18,000 ft^3/s (cubic feet per second), or approximately the average annual flow of the Willamette River at Salem. In the lowland, average annual recharge was 16 in/yr. Generally, recharge is greater in the higher elevations where precipitation is greater. As a percent of precipitation, recharge varied little, from a low of 27 percent of precipitation recharging the lowland to a high of 31 percent in the Coast Range.

Simulated recharge estimates were generally proportional to precipitation. Recharge estimates were higher than expected in the Coast Range and Western Cascade area where precipitation is high but steep slopes and low permeability bedrock promote runoff and reduce infiltration. PRMS overestimates recharge in these areas because once water infiltrates past the soil zone in the model, it is assumed to be recharge. In the Coast Range and Western Cascade area, however, water probably infiltrates to a shallow depth before discharging to streams within these regions. From a regional perspective, this infiltration is not recharge but shallow flow in the soil zone. High rates of recharge are reasonable in the High Cascade unit because of permeable material at the surface, high precipitation rates, and an undeveloped stream network (Ingebritsen and others, 1992). Most recharge in the Coast Range, Western, and High Cascade areas eventually discharges to streams within those regions and is unavailable as ground-water inflow to the lowland. Consequently, recharge to the lowland area occurs locally and is the source of water for most ground-water resources in the lowland.

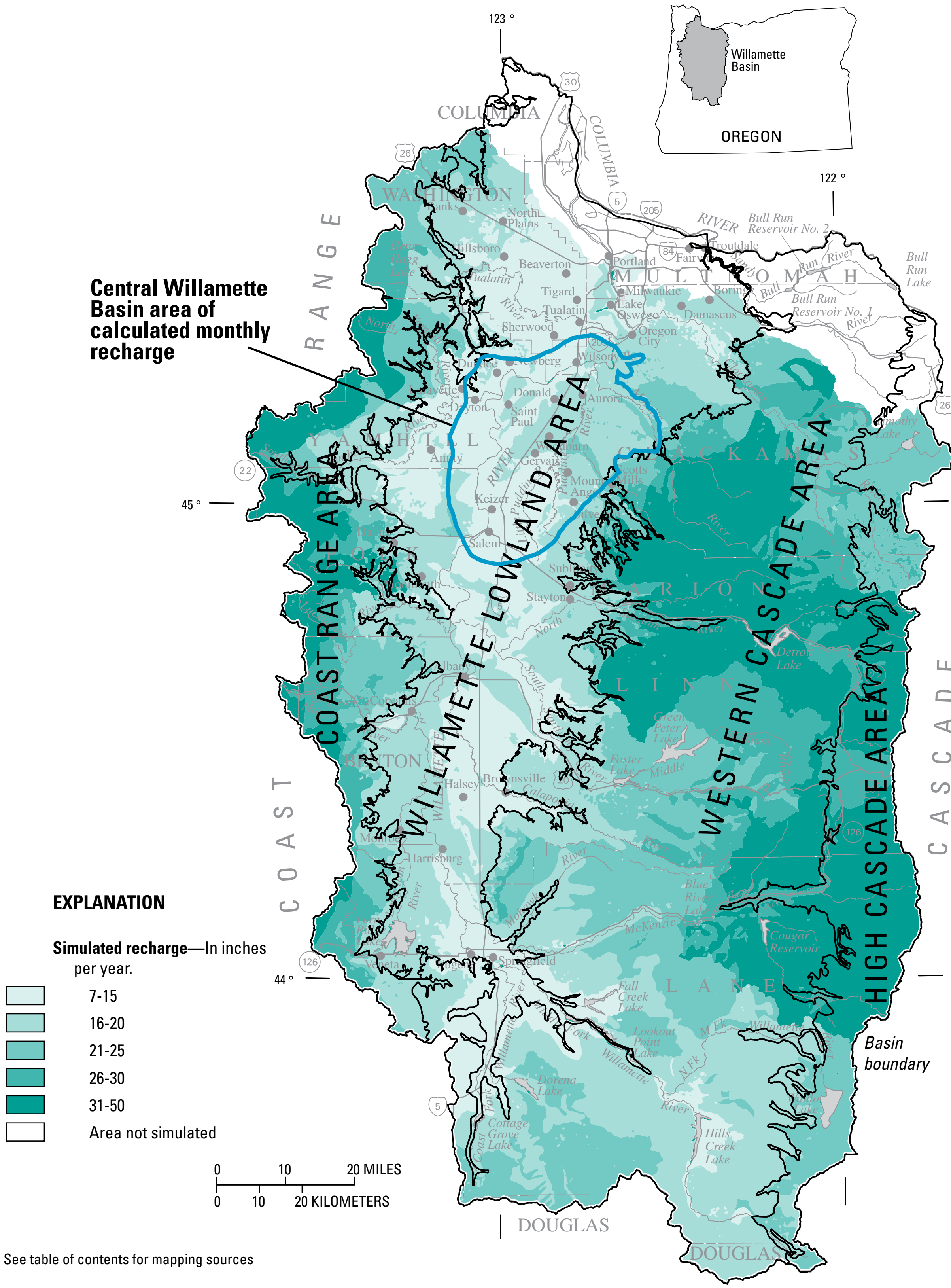


Figure 12. Simulated annual recharge, Willamette Basin, Oregon, 1995–96.

In the lowland area, simulated recharge is low because precipitation is less than in the mountain ranges. Recharge in lowland areas, where the permeable upper and middle sedimentary units are at the surface, is expected to be greater than in lowland areas underlain by less permeable units of the Willamette silt and the lower sedimentary units. The relatively young age of ground water in areas underlain by the upper sedimentary unit (Appendix B) suggests that the ability of water to infiltrate and recharge the ground-water system is greater than in areas underlain by the less permeable Willamette silt unit.

Recharge into the Willamette silt unit may be facilitated by ponding of precipitation on the flat surface of the unit. Although the low permeability of the unit inhibits recharge relative to more permeable units, standing water is available for recharge during much of the wet winter months. For the purpose of analysis, recharge simulated by PRMS will be used to compare components of the ground-water budget with the understanding that recharge may be overestimated in the Coast Range and Western Cascade area.

Recharge varies seasonally because of the large seasonal variation in precipitation. This variation (fig. 13) is shown for the central Willamette Basin (fig. 12) for water year 2000. Fall precipitation replenished soil moisture in the unsaturated zone. By November, soil moisture capacity was exceeded and recharge occurred. Although precipitation declined from November to December, recharge continued to increase because soil moisture was at capacity and precipitation was available for recharge and runoff. Recharge declined in February and March with decreasing precipitation. By April, evapotranspiration and runoff had consumed any additional precipitation, resulting in no recharge. An increase in precipitation in May resulted in a small amount of recharge. After May 2000, evapotranspiration and runoff consumed the modest amount of precipitation and soil moisture. A reduction in evapotranspiration occurred in July and August as soil moisture was depleted. Consequently, recharge was greatest in the wet, winter months and declined to zero in the dry, summer months, when evapotranspiration is large and precipitation is low.

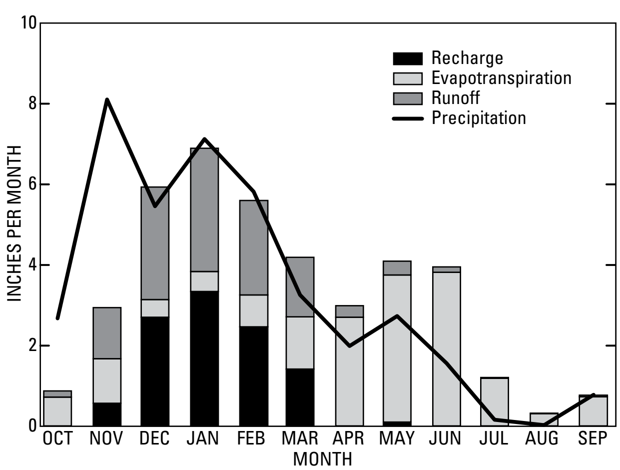


Figure 13. Simulated monthly water budget for water year 2000, central Willamette Basin, Oregon.

Interaction between Surface and Ground Water

Water exchanges, or seepage, occur between the ground-water system and surface-water bodies, such as streams. When the elevation of the stream is above the water table, a downward hydraulic gradient exists and stream water can seep downward to the underlying ground-water system, resulting in a losing stream. Conversely, the elevation of the water table may be above the elevation of the stream, resulting in ground-water seepage upward into the stream, resulting in a gaining stream. Losing streams provide recharge to the ground-water flow system, and ground-water discharge to gaining streams provides an important component of streamflow.

Regionally, streams in the High Cascade area show evidence that ground-water discharge to streams contributes a large proportion to streamflow (Ingebritsen and others, 1992, 1994; Woodward and others, 1998; Gannett and others, 2001; Lee and Risley, 2002; Tague and Grant, 2004). For these ground-water dominated streams, such as the Clackamas River at Big Bottom (USGS site number 14208000), the relatively constant ground-water discharge sustains summer flows and results in seasonal variation in streamflow of less than 50 percent of mean annual flow (fig. 14). Baseflow, which is a measure of the contribution of ground water to streamflow, is estimated to be more than 80 percent of streamflow for streams draining the High Cascade area (Lee and Risley, 2002). Because of the ability of the permeable High Cascade unit to absorb and store water, streams that originate in the High Cascade area provide a large portion of the summer flow to the Willamette River in the lowland (Woodward and others, 1998).

For runoff dominated streams of the Western Cascade area, lowland and Coast Range, such as the Little North Santiam, Molalla, and Luckiamute Rivers, streamflow is flashy, summer flows are small, and the seasonal variation is greater than 100 percent of mean annual streamflow (fig. 14). Baseflow as a percent of streamflow is 50 to 80 percent, considerably less than in streams draining the High Cascade area (Lee and Risley, 2002). Streams in the Coast Range and the Western Cascade area have high precipitation and snowfall, but drain older geologic areas with low permeability and more deeply incised streams resulting in a higher proportion of precipitation becoming surface runoff.

The remaining discussion of the interaction of surface and ground waters is focused in the lowland, where ground-water development is widespread. In the lowland, ground water discharges to streams but its contribution to annual streamflow is relatively small. During the rainy winters, both runoff and ground-water discharge contribute to streamflow. In the dry summers, ground water is the main component of streamflow and discharges at a low rate to streams. As ground-water levels decline during summer, ground-water discharge

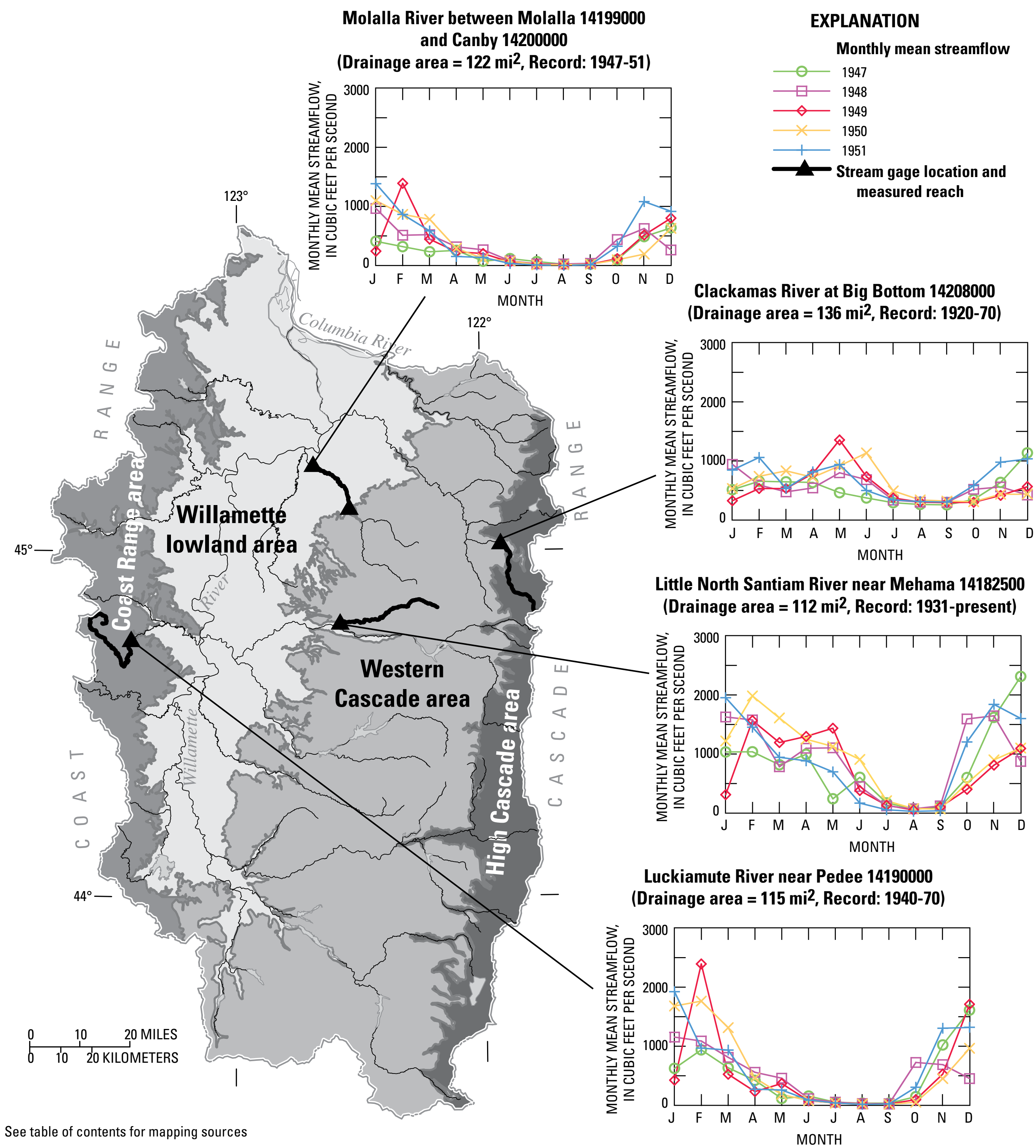


Figure 14. Mean monthly flow of streams of similar drainage area for period when measurements available for all sites, Willamette Basin, Oregon.

to streams decreases. Several methods were used to evaluate the interaction of ground and surface waters and how these exchanges are affected by the permeability of the material underlying the streams, such as the permeable upper and middle sedimentary units and the less permeable Willamette silt unit.

In the lowland, seepage runs, where seepage is calculated from the difference in streamflow at two points along a stream reach (Riggs, 1972), indicated that seepage was small relative to streamflow. In many instances, the calculated seepage was less than the uncertainty in the measurement (5 percent). Seepage was calculated for individual reaches and summed over adjacent reaches (Appendix C) to determine if seepage was greater than measurement uncertainty at different scales. Seepage values are shown in figures 15 and 16 at the scale where seepage is greater than measurement uncertainty. Where seepage is less than measurement uncertainty along individual reaches and cumulatively over many reaches, the entire length of the measured stream is shown without seepage values.

Seepage runs were conducted during low (summer and fall) and high (spring) flow conditions (Lee and Risley, 2002, and Appendix C). Streams gained in most reaches where seepage was greater than the measurement uncertainty and stream diversions were quantified (fig. 15 and 16). During low flows, the smaller streams that flow in a northwesterly direction along the eastern edge of the central Willamette Basin (Butte, Abiqua, and Drift Creeks) lost water in the upstream reaches and gained water in the downstream reaches (fig. 15); however, irrigation withdrawals from these streams were not quantified and could account for the apparent stream losses. The alternating gains and losses in the South Santiam (Appendix C) and Willamette Rivers (fig. 15, Appendix C), although less than the uncertainty in some of the measurements, may indicate shallow flow along short flow paths between the stream and the gravels of the streambed and adjacent floodplain (Laenen and Risley; 1997, Woodward and others, 1998; Hinkle and others, 2001; Laenen and Bencala, 2001; Fernald and others, 2001).

Gaining reaches throughout the lowland are consistent with the shape of shallow water-level contours (pl. 1). Most water-level contours bend upstream as they cross streams within the lowland indicating gaining stream reaches. The upstream bend of the contour is gentle across the broad, shallow floodplains of the Willamette River and major tributaries which are underlain by permeable upper sedimentary unit. The bend of the water-level contours is sharp across the deep narrow floodplains of the smaller streams underlain by less permeable Willamette silt unit, especially in the central Willamette Basin.

Gaining reaches were confirmed by comparing water levels in wells near streams to stream stage. Upward hydraulic gradients confirmed gaining reaches in streams flowing over the upper sedimentary unit (well 12S/05W-02AAA near Corvallis) and the Willamette silt unit (wells 04S/02W-01CDD01 and 05S/01W-28CCD02) (pl. 1).

Water levels in shallow wells near large streams (wells 11S/05W-35DDD and 06S/03W-04ACD) track stream stage, indicating a good hydraulic connection between the stream and the underlying upper sedimentary unit. Stream water is easily stored in the permeable bank during extremely high flows and ground water readily discharges to these regional discharge areas during most of the year.

The rate of ground-water discharge to streams flowing on the Willamette silt unit at six sites was estimated with seepage meters and by simulating one-dimensional heat transport (Conlon and others, 2003). Seepage meters estimate seepage by measuring the change in volume of water entering or leaving a bag connected to an open-ended steel drum pushed into the streambed (Lee and Cherry, 1978). Seepage is estimated with heat transport modeling by simulating the vertical flow beneath a stream necessary to match simulated to observed streambed temperature gradients (Niswonger and Prudic, 2003). The gains were small, ranged over two orders of magnitude, and provide a constraint of the ground-water discharge to streams flowing over the Willamette silt unit (table 3).

The small gains to streams flowing on the Willamette silt unit are due to the poor hydraulic connection between the streams and the underlying ground-water system. This poor connection is a result of the low hydraulic conductivity of the Willamette silt unit. The vertical hydraulic conductivity was estimated using heat transport modeling and ranged from 0.04 to 0.7 ft per day (table 3), which probably represent maximum values. Most ground-water discharge to these streams occurs from the Willamette silt unit and is small relative to streamflow (Iverson, 2002). Upward flow from the middle sedimentary unit is limited by the low vertical hydraulic conductivity of the overlying Willamette silt unit. Similarly, where pumping locally from the middle sedimentary unit lowers ground-water levels below the stream stage, losses of stream water to the ground-water flow system are expected to be small. The ground-water discharge per unit area in streams underlain by the less permeable Willamette silt unit is small (table 3) relative to gains in streams that flow over the permeable upper sedimentary unit.

Quantifying ground-water discharge to streams and stream losses to the ground-water system in the Willamette Basin is difficult. For large streams with permeable streambeds, large gains are expected; however the calculated gains and losses are generally less than seepage run measurement uncertainty because of large flows and flow regulation. For smaller streams with less permeable streambeds consisting of the Willamette silt unit, gains are smaller than the measurement uncertainty, despite the low flow of these streams. Regional ground-water discharge to streams will be estimated as the residual of an annual regional water balance in the section Budget Summary.

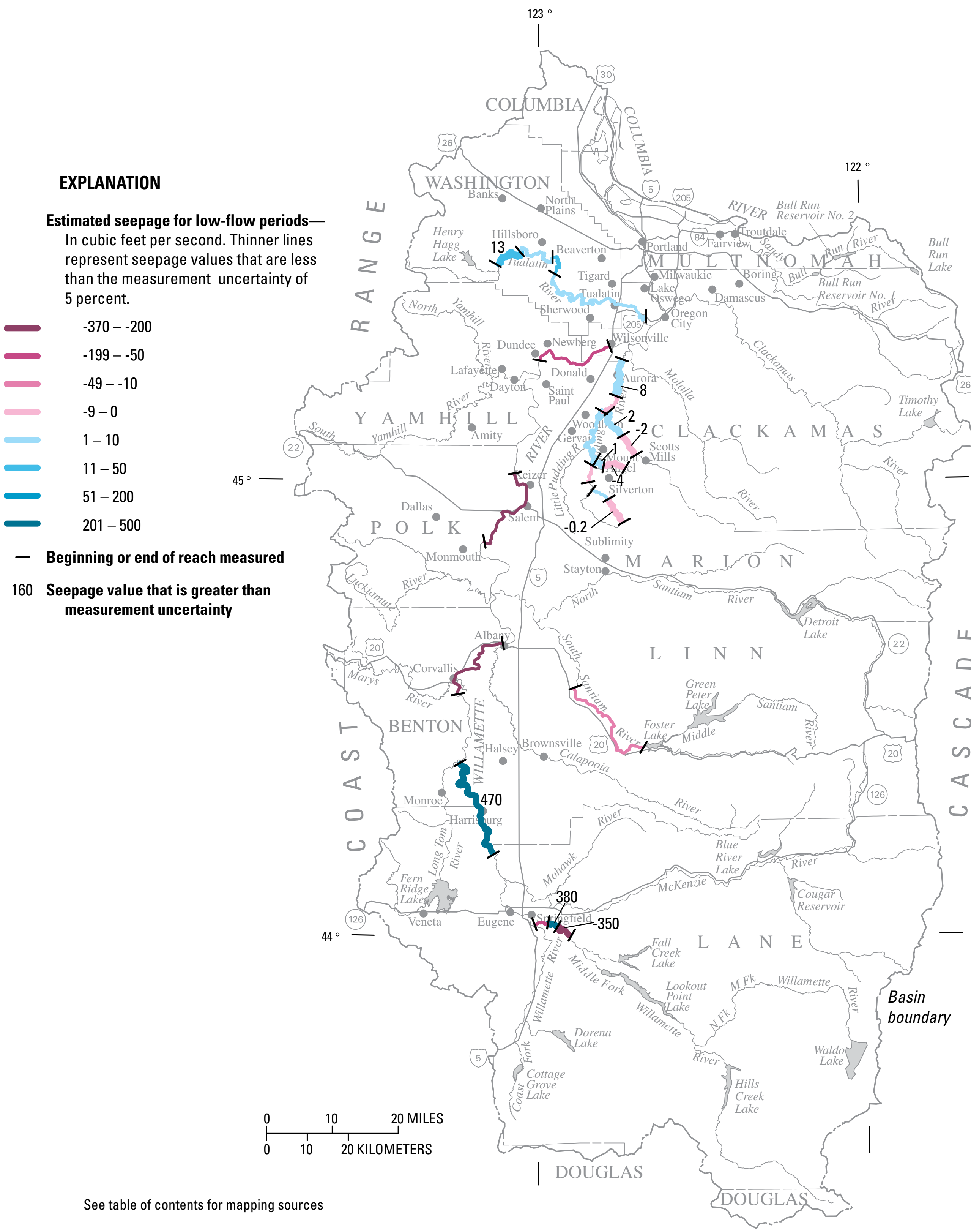


Figure 15. Estimated seepage for selected streams during low flow periods, summer and fall 1993, 1996, and 2000, Willamette Basin, Oregon.

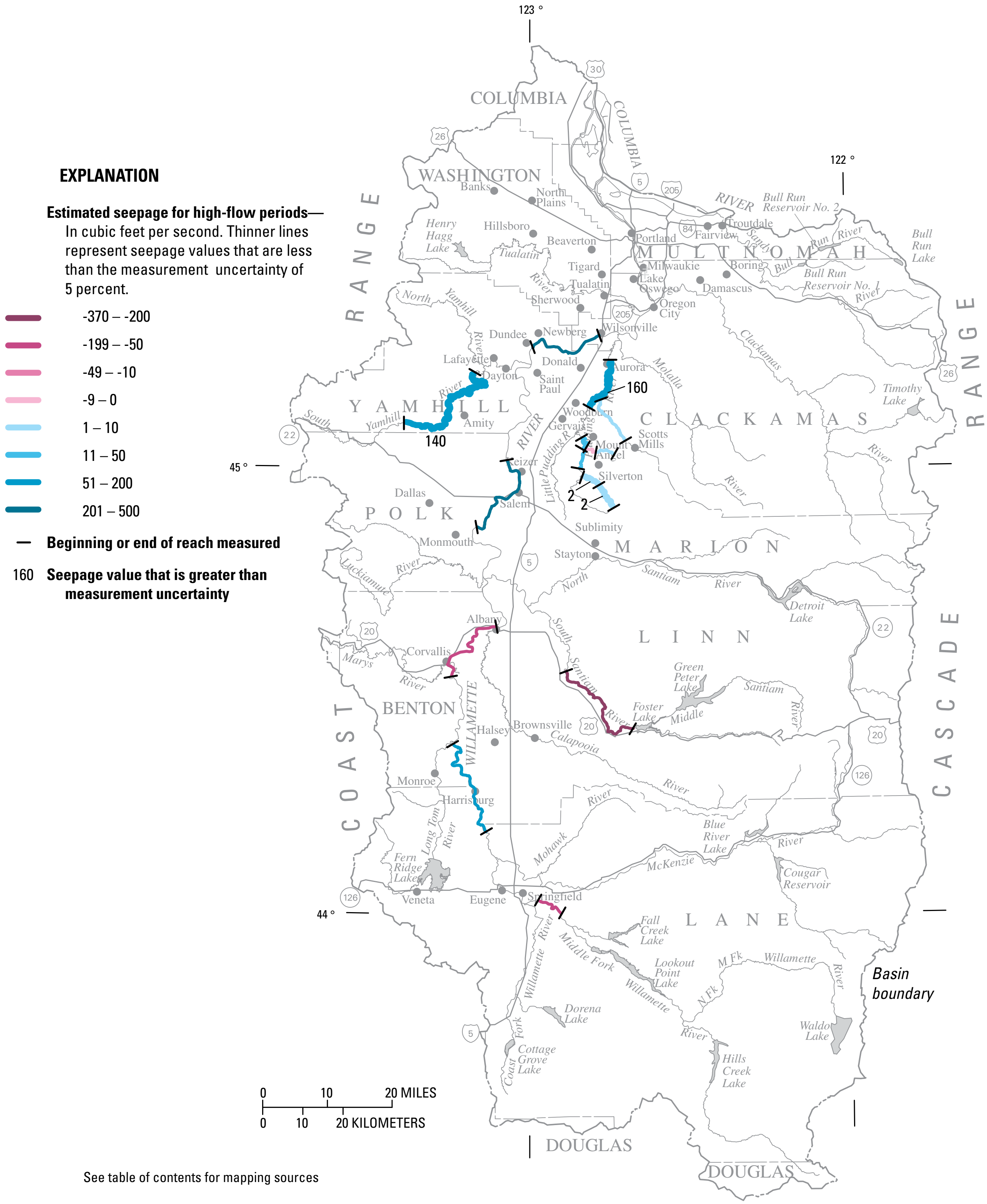


Figure 16. Estimated seepage for selected streams during high flow periods, spring 1996 and 2000, Willamette Basin, Oregon.

Table 3. Selected stream gains and losses in the Willamette Basin, Oregon.

[RM, river mile; WSU, Willamette silt unit; USU, upper sedimentary unit; ft, feet; d, day; Kv, vertical hydraulic conductivity, MF, Middle Fork. Unit gain is calculated by dividing volumetric gain by area over which gain occurs. For seepage runs, the area is the estimated width times the distance between river miles. For seepage meters, the area is the area of the seepage meter drum]

Stream	From RM	To RM	Date	Streambed material	Seepage run unit gain (+) or loss (-) (ft/d)	Seepage meter unit gain (ft/d)	Heat tracing unit gain (ft/d)	Heat tracing Kv (ft/d)	Estimated river width (ft)
Case Creek	at 0.1	na	August 2000	WSU	na	0.003	0.10	0.67	--
Little Pudding River	at 9.0	na	August 2000	WSU	na	0.001	0.02	na	--
Upper Pudding River	at 48.5	na	August 2000	WSU	na	0.006	0.01	0.33	--
Zollner Creek	at 1.0	na	August 2000	WSU	na	0.249	0.01	0.04	--
Lower Pudding River	at 22.5	na	August 2000	WSU	na	0.001	0.17	0.25	--
Butte Creek	at 2.5	na	August 2000	WSU	na	0.004	0.15	na	--
Butte Creek	5.9	1	9/12/2000	WSU	0.15	na	na	na	20
Pudding River	17.5	8.1	9/21-22/2000	WSU	0.29	na	na	na	50
MF Willamette River	195	192.8	7/23/1996	USU	-26.03	na	na	na	200
MF Willamette River	192.8	190.5	7/23/1996	USU	27.14	na	na	na	200
MF Willamette River	169.6	149.6	7/24/1996	USU	3.85	na	na	na	200
Johnson Creek*	3.2	2.2	7/21-22/2000	USU	0.53	na	na	na	50
Crystal Springs Creek*	1.8	0	8/7/2000	USU	4.87	na	na	na	20

* Gains in Johnson and Crystal Springs Creeks result from spring flow over distances shorter than the reach between discharge measurements. Consequently, seepage run unit gain is a minimum value.

Evapotranspiration

Evapotranspiration occurs from the unsaturated zone as water percolates to the water table and from the saturated zone when the water table is within the rooting depth of plants. Evapotranspiration from the unsaturated zone is accounted for in the watershed model PRMS and is discussed in Lee and Risley (2002). Evapotranspiration from the saturated zone is estimated where the water table is within 10 ft of the land surface between April and September.

Of the approximately 5,000 wells considered in this report, 10 percent of the wells had water levels less than 10 ft below land surface. In the central Willamette, Tualatin, and Portland Basins, shallow water levels are limited to the small area containing the floodplains of streams and are assumed to be insignificant. The assumption that evapotranspiration is negligible in these areas is based on a limited data set of wells that are generally completed below the Willamette silt unit in the upper and middle sedimentary units. In the southern Willamette Basin, shallow water levels suggest evapotranspiration is possible from an area of about 1,100 mi^2 (square miles).

The maximum amount of water that could be consumed by evapotranspiration from the saturated zone annually is estimated based on potential evapotranspiration computed by the PRMS watershed models. Lee and Risley (2002) estimated the potential evapotranspiration possible if an unlimited amount of water were available, and the actual evapotranspiration, which reflects the availability of moisture in the unsaturated zone to satisfy potential evapotranspiration. The residual evapotranspiration is the remaining amount of potential evaporation possible from the saturated zone that is not satisfied by actual evapotranspiration at land surface.

The average annual rate of residual evapotranspiration for 1995–96 in the 1,100 mi^2 area in the southern Willamette Basin is 28 in/yr (inches per year). Actual evapotranspiration is less than 28 in/yr because there are no long-term water-level declines as would be expected if the actual evapotranspiration rate in the saturated zone exceeded the recharge rate of 16 in/yr. Actual evapotranspiration from the saturated zone is probably less than the recharge rate of 16 in/yr. For purposes of the water budget, evapotranspiration from the saturated zone is assumed to be 50 percent of the recharge rate in the lowland, or 8 in/yr. Assuming this rate, annual evapotranspiration from the water saturated zone is equivalent to 630 ft^3/s, or 460,000 acre-ft/yr (acre-feet per year). This estimate represents an upper bound on evapotranspiration because (1) the water table is not at or near the land surface, but at some depth below the land surface, (2) plants grown in the area, such as turf grass and grass for grass seed, may have shallow roots that do not extend to the water table, and (3) not all areas within the 1,100 mi^2 area have shallow water levels.

Well Discharge

Most ground-water use in the Willamette Basin falls into four categories: public supply, irrigation, industrial, and domestic. Public supply includes all water distributed by public water utilities within utility boundaries, including water used for drinking, industrial, commercial, and irrigation purposes. Public supply use includes municipal water use. Irrigation use is predominantly rural agricultural crop irrigation but also includes nursery irrigation and some irrigation of golf courses and parks that is not supplied by water utility wells. Industrial use includes ground water pumped from non-public supply wells for manufacturing, food processing, and other industrial or commercial processes. Domestic use refers to pumpage from private domestic wells.

Ground-water withdrawal estimates were made for irrigation, public supply, and industrial use and are described below. Withdrawals were estimated for each hydrogeologic unit and summarized by basin. Annual pumpage for the entire basin was estimated for water years 1995 and 1996. Monthly withdrawals were estimated for the central Willamette Basin for water years 1999 and 2000. Estimates for domestic use were not made because the consumptive portion of domestic use was assumed to be small and because domestic use is assumed to be a small fraction of the regional water budget. Collins and Broad (1996) estimated that about 40 acre-ft/yr (0.6 ft^3/s) of water was pumped for domestic use in the entire Willamette lowland (including Clark County, Washington) in 1990. Consumptive domestic use may, however, be a large component of the local water budget in areas of dense rural residential development, even when land parcels are small, if landowners collectively irrigate substantial areas of lawns, gardens, and pastures. This is more likely to be the case where rural domestic development occurs in upland areas underlain by the Columbia River basalt and basement confining units.

Methods

Estimates of ground-water withdrawals for public supply are based on annual reports of monthly water-use that public-water purveyors submit to the OWRD for each permitted well. Missing data were obtained directly from water suppliers, extrapolated from the reports of previous years with an adjustment for population growth, or estimated from population data.

Industrial water use was estimated using water right data from the OWRD and data from periodic surveys of water-use by the U.S. Geological Survey (Broad and Collins, 1996; Collins and Broad, 1996). Estimates were based on permitted water rates, waste-discharge permits, and supplemental information from interviews with facility operators.

Estimates of ground-water withdrawals for irrigation were based on water right information and satellite imagery because irrigation water use is not reported. Water rights specify a maximum allowable use but do not provide a good indication of actual use in any given year. Crop rotation patterns, changes in land use or ownership, economic considerations, and other factors affect actual water use in any given year or area. Because of these factors, irrigation pumpage was estimated using 1992 LANDSAT satellite images by the following procedure: (1) Land cover by crop type was classified using spectral data from LANDSAT thematic mapper images. (2) Lands irrigated with ground water were determined using water right records. (3) Irrigation water needs were estimated by multiplying these acreages by crop water requirements minus any precipitation that fell during the irrigation season. Where ground water is used to supplement surface-water rights, ground-water withdrawals were assumed to annually account for 50 percent of irrigation water needs on lands. (4) Withdrawals from wells were calculated by dividing irrigation water needs by the irrigation efficiency which was assumed to be 0.75 (King and others, 1978) for the entire basin. Pumpage was assigned to hydrogeologic units based on completion intervals from well logs or based on the hydrogeologic units underlying the well location if a well log was not identified for the water right. Monthly withdrawals were estimated in the central Willamette Basin for 1999 and 2000 by distributing crop water requirements over the growing season for each crop type based on evapotranspiration and precipitation.

Many factors introduce uncertainty into estimates of irrigation water use in the Willamette Basin. For example, many of the crops grown in the basin have similar spectral properties in satellite imagery, but may have substantially different water needs. Small fields, many less than 20 acres in size, and variable crop types increase the difficulty of producing a coherent land-cover classification. In addition, different irrigation methods can result in substantially different amounts of applied water, even for the same crop. This is an important consideration in assessing the water use of the expanding nursery industry where irrigation methods range from hand-line sprinklers, to low-pressure overhead sprinklers, to drip irrigation systems. To assess these factors, extensive field inspections during 1999 were used to evaluate uncertainties in irrigation water-use estimates. The results indicate that irrigated croplands can generally be distinguished from nonirrigated croplands with a high degree of confidence. However, extensive field inspections are necessary to refine land cover classifications to a crop-specific level and to evaluate the impact of varying irrigation methods.

More refined estimates of irrigation water use were made in the central Willamette Basin during 1999 and 2000 by using three sets of LANDSAT images over the irrigation season and by conducting periodic field inspections to verify crop types and irrigation practices. In addition, unlike most other areas in the Willamette Basin, up-to-date digital water right maps were available for the entire central Willamette Basin and well logs were identified for most water rights in the area. Because of these factors, estimated withdrawals in 1999 for the central basin were presumed to be more accurate than those determined during the 1995–96 regional analysis. Estimates made in 1999 were about 60 percent of those made in 1995–96. Because county crop production summaries indicated little change in crop acreages between these time periods, this proportion was assumed to be caused by systematic overestimation of irrigated acreages due to uncertainty in the classification of 1992 satellite imagery in the basinwide estimate. The proportion was also assumed to be typical of the entire Willamette Basin and was used to adjust the basinwide irrigation water use for the 1995–96 period.

Annual Ground-Water Withdrawals in the Willamette Basin in 1995 and 1996

Annual ground-water withdrawals in the Willamette Basin for 1995 and 1996 are summarized in table 4 by category of use, hydrogeologic unit, and drainage basin. Most ground water is withdrawn from permeable units in the lowland (fig. 17). Total pumpage was about 300,000 acre-ft, the equivalent of a mean annual pumping rate of about 400 ft^3/s. This represents 10 percent of annual recharge in the lowland. For comparison, this is equal to about 1 percent of the average annual flow of the Willamette River at Portland (33,400 ft^3/s) and about 32 percent of the average annual flow of the Pudding River at Aurora (1,250 ft^3/s). Of the total withdrawals, 81 percent was pumped for irrigation, 14 percent for public supply, and 5 percent for industrial use. These proportions are typical of all areas except the Portland Basin, which had a smaller proportion of irrigation use (40 percent) and larger proportions of public supply (37 percent) and industrial (24 percent) use, a distribution that is consistent with a larger fraction of urbanized area in the Portland Basin.

About 48 percent of all ground-water withdrawals occurred in the central Willamette Basin, 39 percent in the southern Willamette Basin, 9 percent in the Portland Basin, and 5 percent in the Tualatin Basin. Most pumpage in the central and southern basins was for irrigation, which in these two areas accounted for 74 percent of the total ground-water use in the entire Willamette Basin. Lower pumpage in the Portland Basin reflects the smaller area available for irrigation in the basin and a greater reliance on surface water for public supplies. Pumpage in the Tualatin Basin is limited by the lack of productive aquifers.

Most ground water in the Willamette Basin was withdrawn from basin-fill sediments (86 percent) with lesser amounts pumped from the Columbia River basalt (11 percent) and basement confining units (3 percent). Within the basin-fill sediments, the largest fraction of pumpage was from the middle sedimentary unit with a slightly smaller fraction from the upper sedimentary unit and a much smaller fraction from the lower sedimentary unit.

About 73 percent of all pumpage in the Willamette Basin is from the upper and middle sedimentary unit, most of which is used for irrigation in the central and southern basins. More water is drawn from the middle sedimentary unit in the central Willamette Basin, where wells are widely distributed and thick

Table 4. Mean annual ground-water use in the Willamette Basin, Oregon, 1995–96.

[USU, upper sedimentary unit; MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; BCU, basement confining unit]

Willamette Basin ground-water withdrawals							
	Withdrawals by category		Withdrawals by category and hydrogeologic unit				
Willamette Basin	Pumpage by category (acre-feet)	Percent of Willamette Basin	USU (acre-feet)	MSU (acre-feet)	LSU (acre-feet)	CRB (acre-feet)	BCU (acre-feet)
Irrigation	241,100	81.0%	79,700	104,000	25,900	24,400	7,000
Public supply	42,700	14.4%	9,200	14,900	10,400	6,600	1,600
Industrial	13,700	4.6%	1,500	7,100	3,600	1,300	200
Total	297,500		90,400	126,000	39,900	32,300	8,800
Percent		100.0%	30.4%	42.4%	13.4%	10.9%	3.0%

Ground-water withdrawals by region							
	Withdrawals by category		Withdrawals by category and hydrogeologic unit				
Portland Basin Region	Pumpage by category (acre-feet)	Percent of Subbasin	USU (acre-feet)	MSU (acre-feet)	LSU (acre-feet)	CRB (acre-feet)	BCU (acre-feet)
Irrigation	10,200	39.7%	4,100	5,500	70	500	10
Public supply	9,400	36.6%	30	6,300	2,700	300	0
Industrial	6,100	23.7%	800	3,800	900	600	0
Total	25,700		4,930	15,600	3,670	1,400	10
Percent of subbasin		100.0%	19.2%	60.7%	14.3%	5.4%	0.0%
Tualatin Basin							
Irrigation	11,900	84.2%	0	0	4,700	6,900	300
Public supply	2,000	13.9%	0	0	0	2,000	0
Industrial	300	1.9%	0	0	200	100	0
Total	14,200		0	0	4,900	9,000	300
Percent of subbasin		100.0%	0.0%	0.0%	34.5%	63.4%	2.1%
Central Willamette Region							
Irrigation	123,000	86.1%	16,600	69,400	20,200	14,400	2,500
Public supply	14,300	10.0%	600	2,800	6,700	4,100	4
Industrial	5,600	3.9%	500	2,600	1,900	700	0
Total	142,900		17,700	74,800	28,800	19,100	2,504
Percent of subbasin		100.0%	12.4%	52.3%	20.2%	13.4%	1.8%

Table 4. Mean annual ground-water use in the Willamette Basin, Oregon, 1995–96—Continued.

[USU, upper sedimentary unit; MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; BCU, basement confining unit]

Ground-water withdrawals by region							
	Withdrawals by category		Withdrawals by category and hydrogeologic unit				
Southern Willamette Region	Pumpage by category (acre-feet)	Percent of Subbasin	USU (acre-feet)	MSU (acre-feet)	LSU (acre-feet)	CRB (acre-feet)	BCU (acre-feet)
Irrigation	96,000	83.6%	59,000	29,100	900	2,700	4,200
Public supply	17,100	14.9%	8,600	5,700	1,000	300	1,600
Industrial	1,700	1.5%	200	600	600	0	200
Total	114,800		67,800	35,400	2,500	3,000	6,000
Percent of subbasin		100.0%	59.1%	30.8%	2.2%	2.6%	5.2%

coarse-grained alluvial fan deposits underlie broad areas of the valley floor, compared to thin strips of younger floodplain sediments, which are restricted to narrow floodplains (figs. 4 and 7). A greater proportion of pumpage is from the upper sedimentary unit in the southern Willamette Basin, where wells are concentrated in the Willamette River floodplain.

Only 13 percent of all ground-water withdrawals are from the lower sedimentary unit, and most of these withdrawals occur in the central Willamette Basin, where permeable lenses of sand are common in the upper part of the unit. Almost 90 percent of all pumpage from the Columbia River basalt unit occurs in the Tualatin and central Willamette Basins, mostly for irrigation use. In the central Willamette Basin, most of these withdrawals occur at the eastern margin of the valley floor, where the basin-fill sediments are thin.

The proportion of pumping from each hydrogeologic unit varies considerably between basins because of variations in the geology of each basin. For example, the lack of thick coarse-grained sediments in the Tualatin Basin (figs. 4 and 7) accounts for the small proportion of pumpage from the basin-fill sediments (35 percent) and the large proportion of pumpage from the Columbia River basalt unit (63 percent). Similarly, the absence of the Columbia River basalt unit in most of the southern Willamette Basin results in a small contribution to pumpage from the unit.

Over 10,000 wells irrigate about 240,000 acres of land based on valid primary ground-water rights in the Willamette Basin. However, a significant fraction of these lands are not irrigated in any given year because of crop rotation patterns. About 241,000 acre-ft of ground water was pumped for irrigation use in 1995, 91 percent of which was withdrawn from the central and southern Willamette Basins (table 4). A comparison of estimated pumpage for 1990 (Collins and Broad, 1996) indicates that irrigation withdrawals increased by 32 percent in the southern basin, 12 percent in the central basin, and 170 percent in the Tualatin Basin. A comparison for the Portland Basin was not made because the 1990 report included parts of Clark County, Washington.

Most large cities in the Willamette Basin, including Portland, Salem, Albany, Corvallis, and Eugene, rely principally on surface water for their public water supplies. Many of these cities are located adjacent to major streams that have additional water available for future demands; however, most will increase their reliance on ground-water supplies in the future. For example, the Portland Water Bureau has developed a large well field to supplement surface water in the summer when municipal demands are high and serve as an emergency backup supply. Similarly, Eugene is developing well fields to meet some of their growing water demand. Many smaller cities in the Willamette Basin are largely, or wholly, dependent upon ground water. Most of these cities are adjacent to smaller streams that have a limited capacity to meet future demands. In many cases, ground-water sources are the only available short-term option for meeting future water demands.

In 1995 and 1996, about 42,700 acre-ft of ground water were withdrawn for public supplies in the Willamette Basin from 182 wells serving 51 community water systems (table 4, fig. 17c). Withdrawals were greatest in the southern (17,100 acre-ft) and central (14,300 acre-ft) Willamette Basins and least in the Portland (9,400 acre-ft) and Tualatin (2,000 acre-ft) Basins.

In the Portland and Tualatin Basins, surface water from Bull Run reservoirs supplies most of the municipal needs of the City of Portland and many of its suburbs. Other communities in the Portland Basin rely completely or partially on ground-water sources. Major ground-water users include the cities of Milwaukie, Troutdale, and Fairview, and the Damascus Water District. Most ground water in the basin is pumped from basin-fill sediments, except in Damascus, where some ground water is withdrawn from the Columbia River basalt unit. In the Tualatin Basin, where the basin-fill sediments are predominantly fine grained, all publicly supplied ground water is withdrawn from the Columbia River basalt unit. Major users include the cities of Sherwood, Tigard, North Plains, and Banks, and the Rivergrove Water District near Lake Oswego.

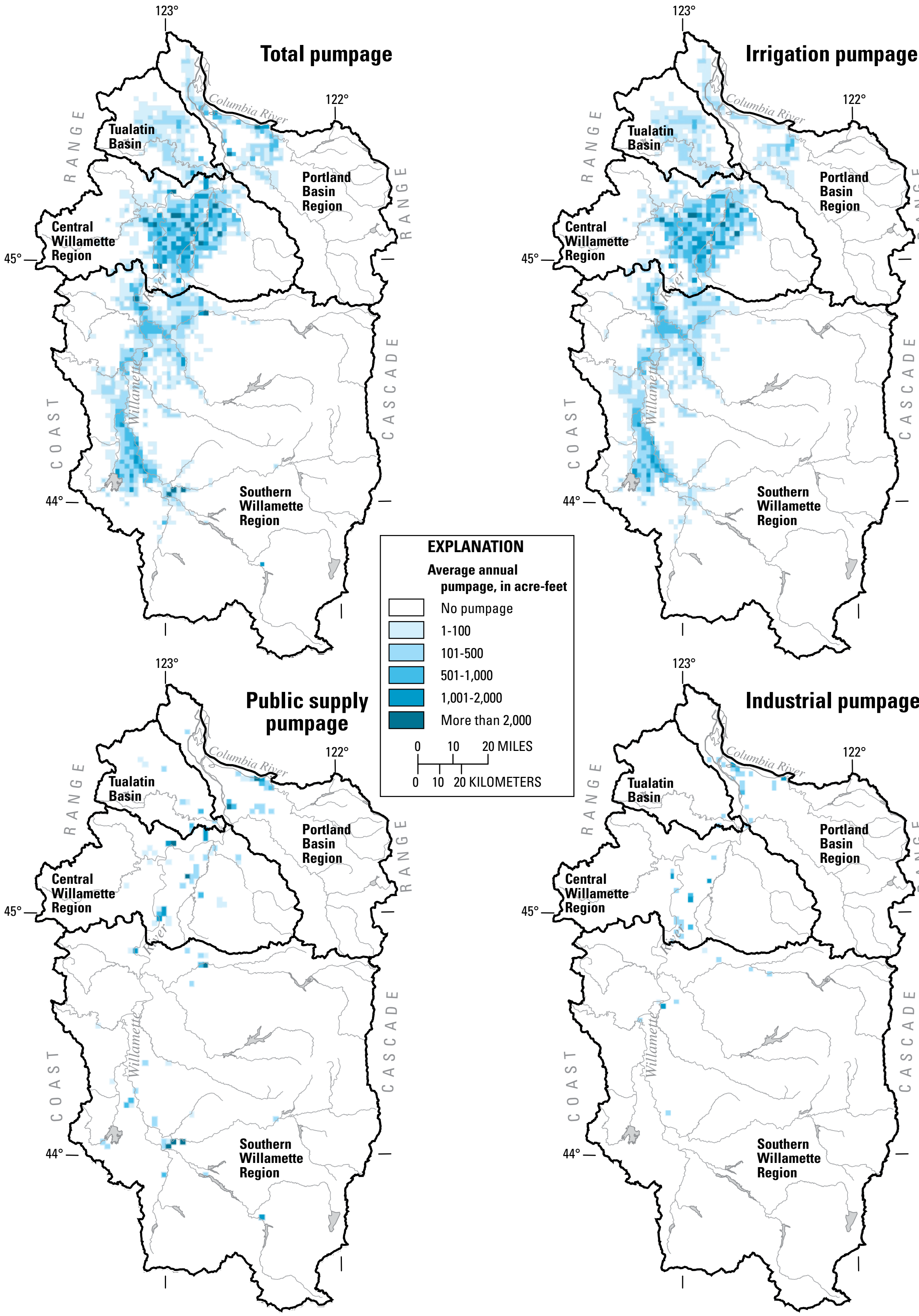


Figure 17. Mean annual ground-water use, 1995–96, Willamette Basin, Oregon.

Except for Salem, most cities in the central Willamette Basin use ground water as their principal source of water. About two-thirds of these withdrawals are from basin-fill sediments and one-third from the Columbia River basalt unit. Major users include Keizer, Wilsonville, Newberg, Woodburn, and Salem. The Cities of Wilsonville, Mount Angel, Dayton, Lafayette, and Scotts Mills withdraw ground water from the Columbia River basalt unit. Because of long-term water-level declines, the City of Wilsonville discontinued withdrawals from the Columbia River basalt unit in 2002 and began using water from the Willamette River as its main source, retaining wells completed in the Columbia River basalt unit as a backup supply.

The Springfield Water Utility Board is the largest ground water user in the southern Willamette Basin. Ground water is also used by Harrisburg, Monroe, Brownsville, Halsey, Veneta, and many other small cities. Almost 90 percent of this pumpage is from the basin-fill sediments.

Industrial withdrawals of ground-water in 1995 totaled about 13,700 acre-ft, about 5 percent of the total ground-water use in the basin. Most of this use occurred at scattered localities in the Portland and central Willamette Basins for food processing, metals, and forest products industries.

Monthly Ground-Water Withdrawals in the Central Willamette Basin in 2000

Annual ground-water withdrawals provide a general gauge for evaluating the impacts of wells on hydrologic systems. However, pumpage impacts can vary greatly within a year if seasonal withdrawals are variable. To assess this variability, monthly ground-water withdrawals were estimated for the central Willamette Basin for the year 1999 (fig. 18). The annual water use of the central Willamette region (table 4) differs from the sum of the monthly water use (fig. 18) because the area of the central Willamette region (fig. 17) differs from the area of the central Willamette Basin (fig. 12). Total ground-water pumpage for the year 1999 was estimated to be about 135,200 acre-ft. About 88 percent of the total was used for irrigation between the months of May and October, 10 percent for public supply, and 2 percent for industrial use. Withdrawals were greatest in the summer and least in the winter. All uses increased during the summer but changes in irrigation use were greatest. The average monthly withdrawal for the year was about 11,300 acre-ft per month. However, from November through April, typical withdrawals were about 900 acre-ft per month mostly for public supply and industrial uses. In contrast, withdrawals in July were about 42,000 acre-ft. Thus, peak withdrawals in July are about 4 times the annual mean monthly withdrawal and about 45 times the typical monthly withdrawal in winter months.

A perspective for comparing seasonal ground-water withdrawals to surface-water flows in the central Willamette Basin can be gained by comparing the monthly equivalents of continuous ground-water pumping rates, in cubic feet per second, to mean monthly streamflows in the Willamette River at Salem and the Pudding River at Aurora (table 5). In the winter months, ground-water withdrawals are equivalent to less than 1 percent of mean monthly flow in the Pudding River and less than 0.1 percent of mean monthly flow in the Willamette River. In July, however, the ground-water withdrawals are equivalent to about 460 percent of the mean July flow in the Pudding River and about 10 percent of mean July flow in the Willamette River. Although mean annual ground-water pumpage is relatively small compared to mean annual streamflow in the Willamette and the Pudding Rivers, ground-water pumpage in the summer is equivalent to a much larger fraction of summer flows in these streams.

Budget Summary

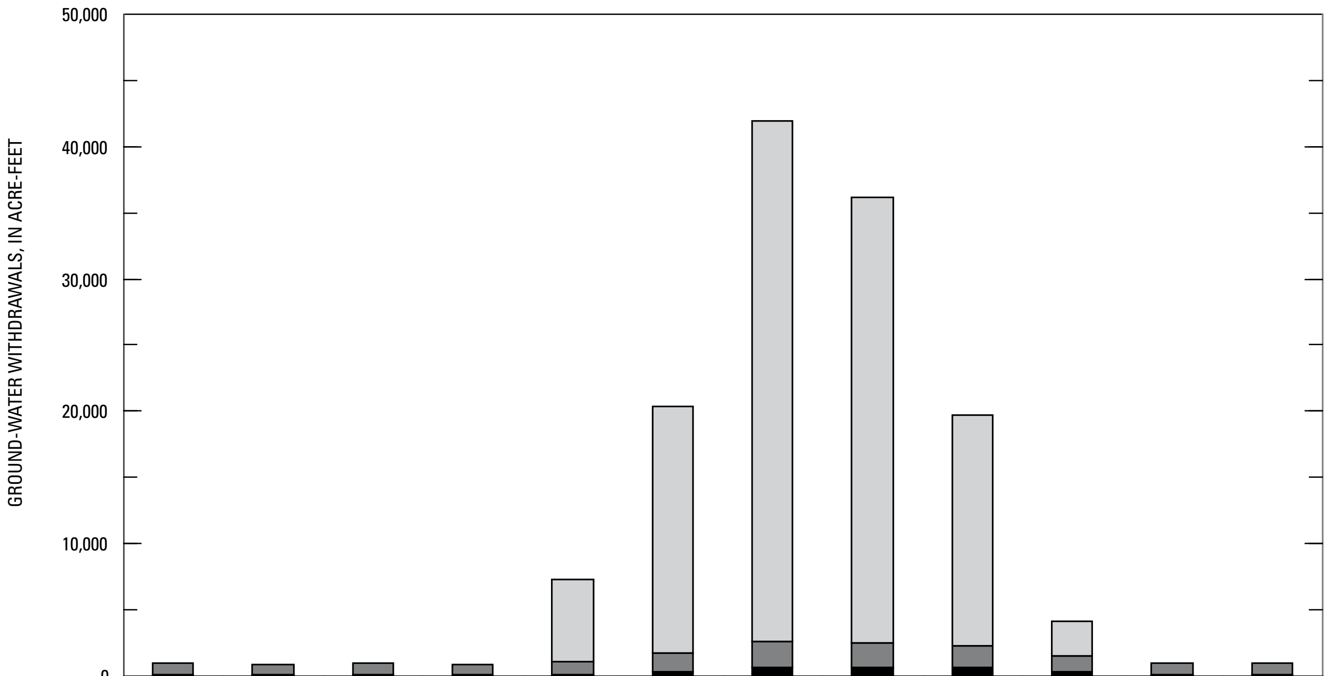
In the previous sections, the components of the hydrologic and ground-water budgets of the Willamette Basin were described and estimated. Although all these quantities are estimated and contain uncertainties, they may be used to estimate a hydrologic and ground-water budget for the Willamette Basin. The following analysis is limited to 1995–96 values for the area within the Willamette Basin modeled using PRMS, which is the area upstream of the Willamette River stream gage at Portland. The area does not include parts of the Portland Basin, including the Sandy River drainage area.

The hydrologic budget, in this report, quantifies how precipitation is divided between recharge to the ground-water system, evapotranspiration from the unsaturated zone, and runoff to streams. The ground-water budget estimates how recharge is divided between evapotranspiration from the saturated zone and discharge to streams and wells. Ground-water inflow to and outflow from the ground-water system are not quantified in the budget. The budgets are computed for three different scales: the Willamette Basin, the lowland portion of the Willamette Basin, and the central Willamette Basin, where ground-water withdrawals are greatest.

Less than one-third (28 percent) of precipitation infiltrates into the subsurface as recharge (table 6). Basinwide, most precipitation is returned to streams as runoff. Within the lowland (fig. 1), where agriculture and warmer temperatures occur, losses to evapotranspiration above the water table are greater than runoff or recharge.

The ground-water budget is poorly constrained because of large uncertainties in evapotranspiration from the water table, seepage to streams, and unquantified subsurface inflows and outflows. Evapotranspiration from the water table is assumed to be 8 in/yr, or approximately half of the lowland recharge rate. Because it was not possible to quantify seepage to streams, it was estimated as the residual of the budget and, therefore, depends on the accuracy of the other components.

In the Willamette Basin, most recharge is returned to streams as ground-water discharge to streams. Ground-water



	Jan 99	Feb 99	Mar 99	Apr 99	May 99	Jun 99	Jul 99	Aug 99	Sep 99	Oct 99	Nov 99	Dec 99
TOTAL	950	850	930	910	7,320	20,390	41,980	36,140	19,690	4,150	940	960
Irrigation	0	0	0	0	6,240	18,640	39,390	33,620	17,450	2,650	0	0
Public supply	890	790	870	830	990	1,460	1,920	1,820	1,620	1,130	860	890
Industry	60	60	60	80	90	290	670	700	620	370	80	70

Figure 18. Monthly ground-water use by category, 1999, central Willamette Basin, Oregon.

Table 5. Mean monthly pumping and streamflow in the central Willamette Basin, Oregon.

[ft^3/s, cubic feet per second]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Ground-water pumpage, in ft^3/s	16	14	16	15	123	343	705	607	331	70	16	16	186
Willamette River flow at Salem (14191000), in ft^3/s (1909–2002)	46,460	40,310	31,920	26,370	20,600	13,950	7,320	5,789	7,129	10,990	28,249	43,140	23,300
Pudding River flow at Aurora (14202000), in ft^3/s (1928–1997)	2,764	2,747	2,111	1,548	880	420	152	70	92	345	1,456	2,482	1,252

Table 6. Hydrologic and ground-water budgets in the Willamette Basin, Oregon, 1995–96.

[M acre-fy/yr, millon acre-feet per year; mi^2, square mile]

	Hydrologic budget					
	Precipitation = Recharge + Evapotranspiration + Runoff					
	Willamette Basin[1] (11,111 mi^2 area)		Lowland (3,394 mi^2 area)		Central Willamette Basin (683 mi^2 area)	
	M acre-ft/yr	Percent of precipitation	M acre-ft/yr	Percent of precipitation	M acre-ft/yr	Percent of precipitation
Precipitation	46.63		10.77		2.09	
Recharge	13.22	28.4%	2.86	26.6%	0.56	26.9%
Evapotranspiration[2]	14.38	30.8%	4.16	38.6%	0.86	41.1%
Runoff	19.03	40.8%	3.75	34.8%	0.67	32.0%

	Ground-water budget					
	Recharge = Evapotranspiration + Well discharge + Stream seepage (storage change assumed negligible)					
	Willamette Basin[1]		Lowland		Central Willamette Basin	
	M acre-ft/yr	Percent of recharge	M acre-ft/yr	Percent of Recharge	M acre-ft/yr	Percent of Recharge
Recharge	13.22		2.86		0.56	
Evapotranspiration[3]	0.46	3.4%	0.46	15.9%	0.00	0.0%
Well discharge	0.28	2.1%	0.28	9.8%	0.14	25.0%
Stream seepage	12.49	94.4%	2.13	74.3%	0.42	75.0%

[1]Upstream of Portland stream gage.

[2]Evapotranspiration from land surface and unsaturated zone simulated with PRMS.

[3]Evapotranspiration from water table (saturated zone) estimated in southern Willamette Basin to be 8 in/yr.

withdrawals by wells are small, only 2 percent of total basinwide recharge. The basinwide budget does not reflect ground-water availability within the lowland because (1) recharge in the Cascade and Coast Ranges discharges to streams within those areas and is not available as ground water in the lowland, and (2) ground-water withdrawals and evapotranspiration are concentrated in the lowland.

Assuming no subsurface inflow to or outflow from the lowland, ground-water seepage to streams accounts for 74 percent of the recharge entering the lowland. Evapotranspiration losses from the water table represent 16 percent of lowland recharge. Ground-water withdrawals within the lowland account for 10 percent of lowland recharge. In the central Willamette Basin, ground-water withdrawals are approximately 25 percent of local recharge, and ground-water discharge to streams accounts for 75 percent of recharge, assuming no subsurface inflow or outflow and no evapotranspiration from the water table in this area.

Ground-water discharge to streams is approximate and calculated as a residual of the ground-water budget. Based on limited data described previously, ground-water discharge to streams occurs throughout the basin, but is expected to be greater to streams in the High Cascade area and the streams flowing over the upper and middle sedimentary units in the lowland than to streams underlain by the low permeability basement confining unit, lower sedimentary unit, and Willamette silt unit.

Ground-Water Elevations and Flow Directions

Ground water flows from areas of high hydraulic head (high water-level elevation) to areas of low head (low water-level elevation). Because hydraulic heads vary laterally and vertically in a ground-water system, ground-water movement will generally have a vertical as well as a horizontal component. Contour maps of heads in aquifers are constructed to determine the horizontal direction of flow. The vertical component of flow can be determined by comparing water levels in nearby wells completed at different depths in the same aquifer or in different aquifers.

A contour map of the water table represents the elevation of the top of the saturated part of the uppermost unconfined aquifer. The horizontal direction of ground-water flow is generally perpendicular to the contour lines and water flows down the slope of the contours in a manner analogous to the flow of water down the slope of the land surface. An accurate map of the water table is constructed from water levels measured in wells that are open to a small interval at the water table. In practice, water-table maps are constructed from water levels measured in wells open over a range of intervals at or below the water table that represent a mixture of heads that are close to, but not at, the elevation of the water-table surface.

If a well is completed in an aquifer confined by overlying materials of low permeability, ground water in the aquifer may be under sufficient pressure to cause the water level in the well to rise above the top of the aquifer. A contour map of heads in a confined aquifer defines a water-level surface that shows the horizontal direction of flow in the confined aquifer. Because hydraulic heads can vary with depth, water-level maps based on measurements from wells completed at different depths or completed in different confined aquifers will reflect some mixture of horizontal and vertical gradients.

Horizontal Ground-Water Flow

Two water-level contour maps were constructed to determine horizontal ground-water flow directions in the Willamette Basin: a water-table map for the basin-fill sediments, and a generalized water-level map for the Columbia River basalt unit. Because water levels vary over time, the maps were largely constructed using measurements from more than 400 wells made during a 2-week period in mid-November 1996, a time of year during which ground-water levels generally approximated average annual water levels. Water levels in many wells were measured prior to heavy rains that fell during the second week of the measurement period. Water levels in most areas rose less than 10 ft in response to the rain event. Therefore, water-level maps based on these measurements are considered to be representative of average annual conditions. Water-level contours were not constructed for most of the Portland Basin because few wells were measured and detailed water-level maps are available in a previous study (McFarland and Morgan, 1996).

Shallow Basin-Fill Sediments

A water-table map for the basin-fill sediments (pl. 1) was constructed using water levels measured in shallow wells, typically less than 150 ft deep, open to the Willamette silt and upper, middle, and lower sedimentary units. Contours were also constrained by water levels from other shallow wells if measurements were made during late October through early December in any year from 1986 to 2000, and if long-term observation wells in an area showed consistent water levels over that same time interval. Stream-stage elevations were used to determine where water-level contours crossed streams.

Where water-level information was not available, the water-table elevation was estimated relative to land surface. The water table is found within 5 to 20 ft of the land surface in the upper sedimentary and Willamette silt units in most areas of the central and southern Willamette Basin, and in the lower sedimentary unit in the Tualatin Basin based on monitoring wells for water-quality assessments and wells measured as part of this study. Because few measured wells are open to the Willamette silt unit, water-table elevations in this unit were estimated using water levels from shallow wells completed in the underlying sedimentary units. The water table will be higher than water levels measured in these shallow wells because, according to drillers' reports and well data, hydraulic heads decrease with depth in the lowland. In the southern Willamette Basin, where the Willamette silt unit is generally less than 20 ft thick, average annual water levels in shallow wells completed in the underlying middle sedimentary unit are generally within 10 ft of land surface, which closely approximates the water table in the silt. In the central Willamette Basin, where the silt unit is up to 120 ft thick, water levels in the silt can be 10 to 25 ft higher than those in shallow wells completed in the underlying sediments (Iverson, 2002). This difference is consistent with the low vertical permeability of the Willamette silt unit, which provides a resistance to vertical flow that results in high water-table elevations relative to water levels in underlying units. Consequently, where the silt is thick, water levels in shallow wells completed in underlying sedimentary units will underestimate the elevation of the water table, but errors will generally be less than 25 ft.

Although Piper (1942) recognized that the water table occurred in the Willamette Silt in the central Willamette Basin, he described shallow ground water in the silt as "semi-perched," which suggests that an unsaturated zone occurs below the water table. However, piezometer and monitoring well data from ground-water quality assessments indicate that the regional water table generally occurs at shallow depths in the silt and that all sediments are fully saturated below this surface.

The regional pattern of ground-water flow is from the margins of the lowland towards the major streams (pl. 1). Ground-water discharge to streams is indicated where contours bend upstream. The change in hydraulic head per unit horizontal distance, referred to as the horizontal hydraulic gradient, is represented by the slope of the water table. Closely spaced contours of equal interval indicate a steep hydraulic gradient (steep slope), whereas widely-spaced contours indicate a flat hydraulic gradient. The velocity of ground-water flow is proportional to the hydraulic gradient if the hydraulic conductivity and effective porosity are constant.

In the southern Willamette Basin, shallow ground water flows from the southeast to the northwest in much of the basin and from east to west in the Stayton Basin. Hydraulic gradients are relatively flat, generally less than 15 ft/mi (feet per mile), because of the gently sloping land surface and relatively high permeability of the upper and middle sedimentary units near land surface. Contours are generally perpendicular to streams, indicating that most ground-water flow is nearly parallel to streams. Although ground water discharges to streams throughout the southern basin, focused ground-water discharge is expected where the Willamette River is constricted to a narrow trench cut into low permeability materials of the basement confining unit near Albany. This is consistent with water-table contours in the 12-mile reach between the Marys River and the gap at Albany, where the contours bend upstream and are nearly parallel to the Willamette River, indicating flow toward, and discharge to, the river. Focused ground-water discharge is expected in a similar gap at the confluence of the North and South Santiam Rivers.

Chlorofluorocarbon (CFC) age dates of shallow ground water (Appendix B) are consistent with flow directions indicated by the water-table contours in the southern Willamette Basin. Samples were collected from shallow wells in the upper and middle sedimentary units along a flow path from the east edge of the valley floor to the floodplain of the Willamette River near Corvallis (fig. B1). Young water (25 years old or less) was found at the eastern edge of the lowland where local recharge is the principal source of inflow to the shallow ground-water system. Older ground water was generally found to the west, consistent with longer flow paths although ages were variable (16 to more than 57 years old) suggesting mixing with younger water. This is to be expected since recharge from precipitation occurs throughout the valley floor. Young ground water (26 years old), found in the upper sedimentary unit at the end of the flow path, may represent the influx of precipitation and surface water into the highly permeable floodplain deposits adjacent to the Willamette River.

Shallow ground-water flow patterns are more complex in the central Willamette Basin because small streams incised up to 50 ft into the Willamette silt unit have a greater effect on shallow water levels than the less incised streams in the southern basin. Most small streams in the central basin, such as the Pudding River and Champoeg Creek, occupy deep, narrow, linear trenches cut into the Willamette silt unit. These stream trenches are separated by relatively flat surfaces that form the typical valley floor at the top of the Willamette silt unit. In general, the trenches do not fully penetrate the silt except near their confluence with the Willamette or Mollala Rivers.

In the areas between streams, the water table generally occurs at depths of less than 15 ft within the silt, and hydraulic gradients are typically between 20 to 40 ft/mi. Gradients steepen adjacent to the steep cutbanks that form the walls of entrenched stream drainages (Iverson, 2002) and near the steep-walled erosional margins of the unit adjacent to the Willamette River floodplain as the water table drops to the level of the streams. The steep hydraulic gradients adjacent to most small streams in the central basin are probably 500 ft/mi within 200 ft of the stream, which is not depicted on the water-table map in plate 1.

The configuration of the water table in the central Willamette Basin produces a number of local flow systems in the Willamette silt unit in which ground water flows from local topographic highs between stream drainages towards adjacent streams. This pattern indicates local recharge in the silts, a component of horizontal flow within the silts towards local streams, and discharge to local streams. Discharge to these smaller streams is limited by the low permeability of the silt. Because there is little resistance to flow in the more permeable sediments of the upper sedimentary unit, hydraulic gradients are relatively flat in the floodplain of the Willamette River, typically less than 2 ft/mi.

In the basin-fill sediments in the Tualatin Basin, the water table generally occurs at depths of less than 20 ft. Ground water flows from the margins of the Tualatin Basin to the center of the basin, where it discharges to streams. Hydraulic gradients are steep because the water table is in the lower sedimentary unit, which has low permeability. Although regional discharge is to the Tualatin River, contours indicate a component of local discharge to tributaries of the Tualatin River.

The elevation and direction of flow indicated by the water table in the sediments of the central and southern Willamette Basins has not changed appreciably since it was first mapped in 1935 (Piper, 1942). This indicates that average annual water levels have generally remained constant in this area since 1935 in spite of the large increase in annual ground-water pumpage over that same span of time. Graphs showing a general absence of long-term decline of water levels discussed in the next section further illustrate this point. Near Woodburn, long-term graphs of water levels indicate a possible decline of less than 10 ft in the water table.

Deep Basin-Fill Sediments—Central Willamette Basin

In the central Willamette Basin, where the Willamette silt unit is thick and confines the underlying permeable deposits of upper sedimentary unit, water levels in the middle sedimentary and lower sedimentary units differ from those of the water table. The change in water levels with depth is gradual, that is, water levels in the upper part of the upper sedimentary unit are similar to the water table, and water levels in the lower part of the upper sedimentary unit and upper part of the lower sedimentary unit represent the water levels of a confined aquifer. Ground water in the confined basin-fill aquifer in the central Willamette Basin likely flows to the Willamette River and the lower reaches of the Pudding and Molalla Rivers, where the confining Willamette silt unit has been removed by stream incision. Because few wells are selectively open to the lower part of the upper sedimentary unit, a water-level map of the confined basin-fill aquifer is not available.

The aquifer consisting of the middle sedimentary unit is confined by the Willamette silt unit and has a poor connection to smaller streams. This pattern of flow was recognized by Piper (1942, p. 35) who described the deeper confined unit as "deep pervious beds that pass below the floors of the stream trenches." Aquifer tests and the response of water levels to precipitation and pumping also suggest that the middle sedimentary unit is confined where the Willamette silt unit is present. Although other studies (Price, 1967a; Woodward and others, 1998) suggest that ground water in the middle sedimentary unit in the central Willamette Basin is unconfined and discharges to small streams underlain by Willamette silt unit, hydrologic data collected during this study indicate ground water in the middle sedimentary unit in this area is generally confined and discharges to the Willamette River.

Columbia River Basalt Unit

Water-level data in the Columbia River basalt unit were collected in the Portland, Tualatin, and central Willamette Basins. Constructing a map of water levels in the Columbia River basalt unit presents several problems: (1) measured water levels in the Columbia River basalt unit are not evenly distributed, with many wells open to Columbia River basalt unit at the margins of the basins and relatively few wells in the center of the basin, (2) multiple permeable interflow zones separated by the less permeable flow interiors result in potentially large variations in water levels with depth, and (3) water levels in many wells represent composite heads because the wells have uncased boreholes that are open to multiple permeable interflow zones. Therefore, although water-level maps based on composite heads in the basalts must be interpreted with some caution, some general conclusions about ground-water flow in the basalt unit can be made based on the water-level map shown in figure 19.

The water-level map for the Columbia River basalt unit indicates that ground water in the basalt unit generally moves from upland areas at the basin margins, where the unit is exposed at land surface, towards the basin interiors, where the unit is buried by sediments. The general contour patterns suggest that regional discharge from the unit is to the Tualatin and Willamette Rivers. However, the rate of regional discharge to these streams from the basalt unit is probably low because of the low vertical permeability of the basalts and the great thickness of fine-grained sediments above the basalts (fig. 8). Stream-seepage data (Appendix C) and the occurrence of springs indicate that some ground water in the basalt unit discharges to small streams, such as Drift Creek, that are incised into the basalt unit in upland outcrop areas.

Although the direction of ground-water flow inferred from the contours is reasonable, the close spacing of water-level contours where the unit crops out in upland hills suggest unrealistically high horizontal hydraulic gradients. The contours are based on wells completed at different depths and open to different permeable interflow zones. These unrealistically steep gradients reflect vertical gradients between permeable interflow zones rather than horizontal gradients within an interflow zone or within the basalt unit as a whole. Based on water levels in a small number of wells open to similar basalt interflow zones in the Parrett Mountain (Miller and others, 1994) and Silverton (Marc Norton, OWRD, oral commun., 2004) areas, horizontal gradients in the upland areas are expected to be low, less than 10 ft/mi.

Horizontal gradients beneath the valley floors in the central Willamette Basin near Wilsonville are less than 6 ft/mi based on water-level differences of less than 25 ft in wells that are more than 4 mi apart (fig. 20). Gradients between these wells have decreased by about 50 percent since the City of Wilsonville stopped pumping from the basalt aquifers in late April 2002. This suggests that a significant fraction of the horizontal gradient in the basalts in this area was induced by withdrawals from the City's wells completed in the basalt unit.

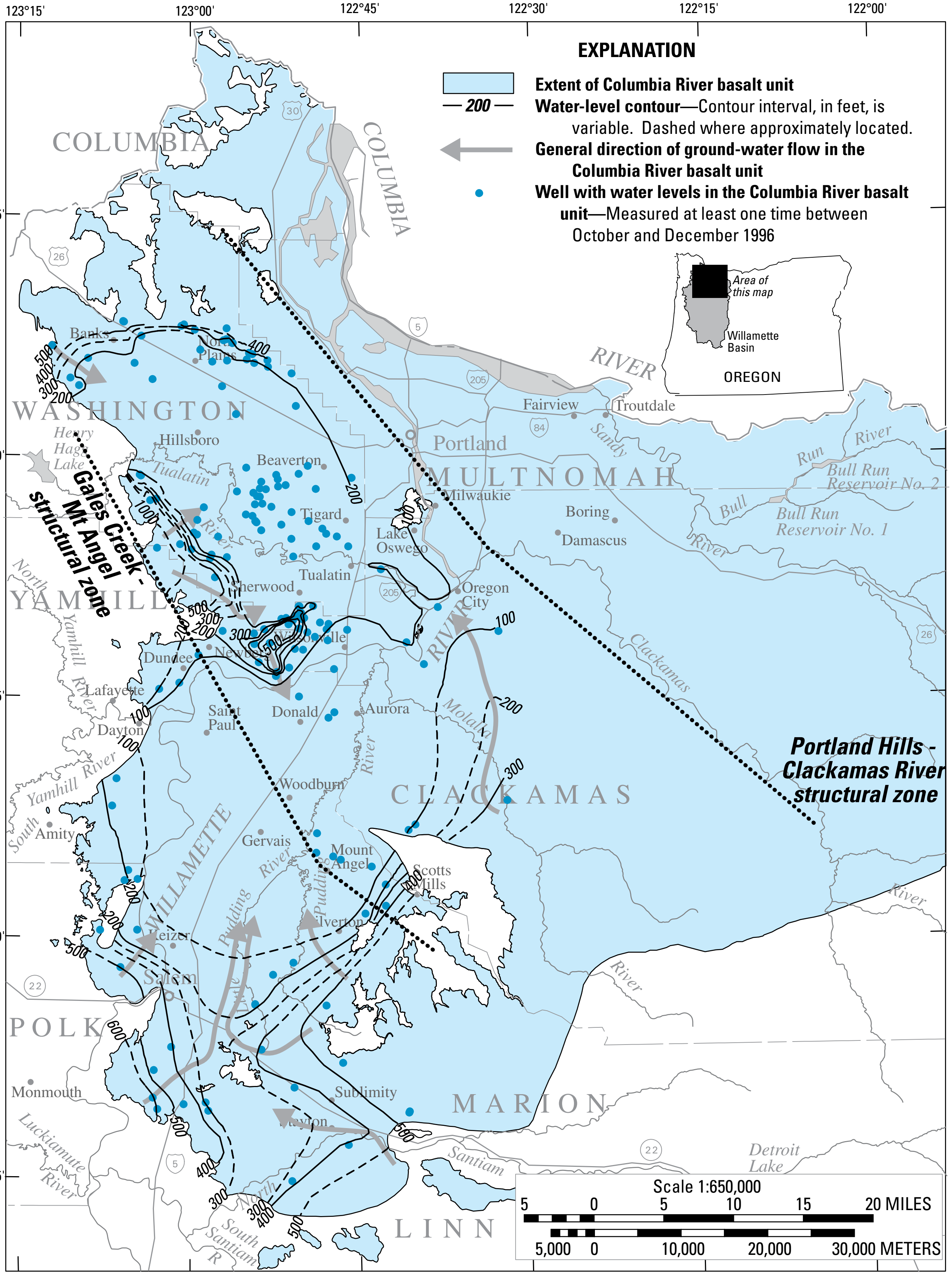


Figure 19. Generalized lines of equal hydraulic head and ground-water flow direction in the Columbia River basalt unit, November 1996, northern Willamette Basin, Oregon.

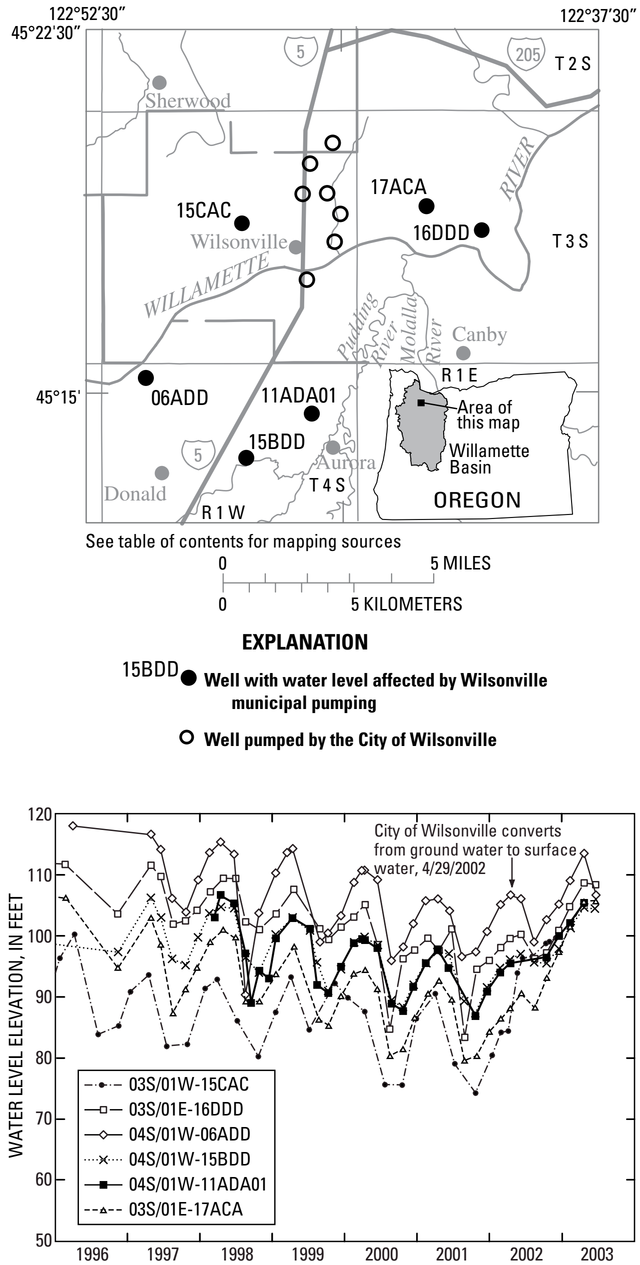


Figure 20. Water levels in wells open to the Columbia River basalt unit near Wilsonville, Oregon, 1996–2003.

These observations indicate that horizontal gradients in the basalt unit were probably no greater than 1 ft/mi under natural conditions. Vertical gradients in the basalt unit appear to be low on the valley floor and most ground-water flow in the unit is essentially horizontal in this part of the system.

Water-level fluctuations and elevations in the deeper zones of the Columbia River basalt unit beneath upland areas are similar to fluctuations and elevations in the basalt unit in the basin. For example, the seasonal fluctuations and long-term decline in water levels in a deep upland well (07S/01W-02CAA01) are similar to those in a well open to the basalt unit in the basin lowland (06S/01W-21CDC02) (pl. 1). Water-level elevations in the two wells differ by less than 15 ft. This similarity suggests a direct connection between deep interflow zones in the uplands and the basin flow system beneath the valley floor.

Various studies suggest that faults can impede horizontal ground-water flow in the Columbia River basalt unit (Newcomb, 1959; Bauer and Hansen, 2000; Reidel and others, 2002) by juxtaposing the thinner, permeable interflow zones against thicker, low-permeable flow interiors or by the formation of a low permeability gouge zones along the fault. It is unclear whether faulting in the Columbia River basalt unit affects horizontal flow on a regional scale in the Willamette Basin. Observations from an aquifer test near Mount Angel indicate that the Gales Creek-Mount Angel structural zone acts as a local flow barrier over short time intervals. Conversely, the regional response of water levels in wells near Wilsonville to changes in pumping suggests that faults, which are likely over this large area, may not act as flow barriers. If faults create barriers to horizontal flow in the basalt unit, they will probably have a large impact on the dynamics of ground-water flow when the unit is stressed by pumping since the propagation of pumping impacts will be limited across these boundaries.

Vertical Ground-Water Flow

Vertical flow in the ground-water system of the Willamette Basin shows a pattern that is generally downward, consistent with recharge areas. Upward flow components are generally limited to narrow zones adjacent to the major stream drainages, indicating ground-water discharge to streams.

The general pattern of downward flow in the basin can be evaluated by comparing water levels in pairs of adjacent wells completed at different depths (fig. 21, table 7). Downward flow, indicated by negative hydraulic gradients, occurs within the basin-fill sediment, between the basin-fill sediments and the Columbia River basalt unit, and within the Columbia River basalt unit in the lowlands.

Within the basin-fill sediments, a downward component of flow is common, with the largest downward gradient, -2.3 ft/ft, found between the less permeable Willamette silt unit and the middle sedimentary unit. An upward component of flow occurs in the narrow drainages of small streams that are deeply entrenched into the Willamette Silt. Upward components of flow in these areas are consistent with flowing wells that are limited to narrow zones coincident with these drainages. However, ground-water discharge to these streams is limited by the low hydraulic conductivity of the Willamette silt unit. Upward ground-water flow also occurs in the basin-fill sediments near the Willamette River, which is a regional discharge area, and where ground-water discharge occurs through the permeable upper sedimentary unit.

The vertical component of ground-water flow between the basin-fill sediments and the Columbia River basalt unit is downward throughout most of the extent of the basalt unit in

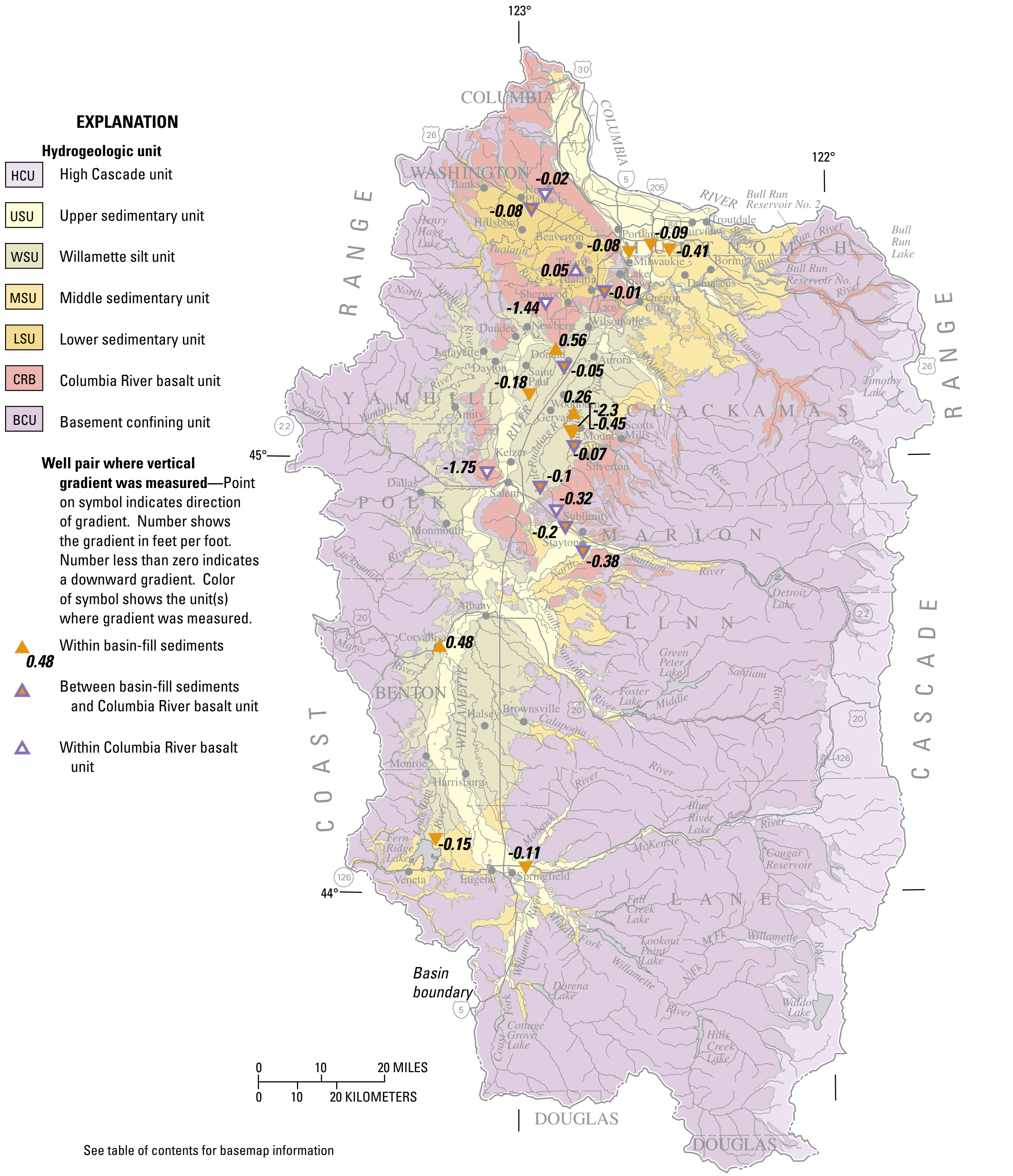


Figure 21. Vertical hydraulic gradients measured in well pairs, Willamette Basin, Oregon.

Table 7. Average vertical hydraulic gradient within and between hydrogeologic units of the Willamette Basin, Oregon, determined by water levels in well pairs.

[OWRD, Oregon Water Resource Department; USGS, U. S. Geological Survey; ft, feet]

Location	OWRD number	USGS site number	Elevation of mid-point of opening (ft above or below (-) NGVD29)	Horizontal distance between wells (ft)	Average vertical hydraulic gradient (ft/ft)
Basin Fill (downward)					
01S/01E-24BBC01	MULT 63238	452827122382401	30.5		
01S/01E-24BBC02	MULT 63239	452827122382402	-33	10	-0.08
01S/02E-13CDA1	None	452840122302202	227.75		
01S/02E-13CDA2	None	452840122302201	190.8	3	-0.41
01S/02E-16BAA01	MULT 63388	452921122340401	144		
01S/02E-16BDA01	MULT 50871	452912122340401	-155	700	-0.09
05S/02W-08CCA2	MARI 52504	450851122575801	57.5		
05S/02W-08CCB1	MARI 52597	450851122580101	-39.5	1,800	-0.18
06S/01W-08DAD06	MARI 55017	450340122493404	119.95		
06S/01W-08DAD03	MARI 54952	450340122493402	94.2	3	-0.45
06S/01W-08DAD04	MARI 54953	450339122492801	113.5		
06S/01W-08DAD05	MARI 55015	450339122492802	100.7	3	-2.30
17S/02W-30CAA2	LANE 10762	440341122584002	428.5		
17S/02W-30CAA1	LANE 10761	440341122584001	340.5	10	-0.11
17S/05W-02BAC2	LANE 3203	440735123154601	365		
17S/05W-02BAC1	LANE 12676	440736123154701	276	160	-0.15
Basin Fill (upward)					
04S/02W-01CDD02	None	451444122524601	71.15		
04S/02W-01CDD01	None	451444122524701	62.45	3	0.56
05S/01W-28CCD01	None	450603122491601	112.25		
05S/01W-28CCD02	None	450603122491602	97.35	3	0.26
11S/05W-35DDD	LINN 10841	443349123150501	183.23		
12S/05W-02AAA	LINN 12120	443348123150201	161.29	300	0.48

Table 7. Average vertical hydraulic gradient within and between hydrogeologic units of the Willamette Basin, Oregon, determined by water levels in well pairs—Continued.

[OWRD, Oregon Water Resource Department; USGS, U. S. Geological Survey; ft, feet]

Location	OWRD number	USGS site number	Elevation of mid-point of opening (ft above or below (-) NGVD29)	Horizontal distance between wells (ft)	Average vertical hydraulic gradient (ft/ft)
		Basin Fill/CRB (downward)			
01N/02W-17ACC	WASH 5382	453417122572901	125		
01N/02W-17DAB	WASH 5377	453414122571001	-501.5	1,000	-0.08
02S/01E-20CBD2	CLAC 3165	452249122430901	73.5		
02S/01E-20CBD1	CLAC 12346	452249122430801	-110	60	-0.01
04S/01W-19ACD01	MARI 54896	451235122510401	55		
04S/01W-19ACA01	MARI 56530	451237122510601	-411.5	300	-0.05
06S/01W-21CDC01	MARI 3280	450140122490701	-1		
06S/01W-21CDC02	MARI 51006	450141122490601	-289.5	100	-0.07
07S/02W-28ADD	MARI 7883	445606122554101	127.5		
07S/02W-28ADD01	MARI 55258	445604122554501	-54	300	-0.10
08S/01W-30DDB1	MARI 8999	445032122505001	353		
08S/01W-30DDB2	MARI 8971	445033122505101	242	140	-0.20
09S/01W-15DCB01	LINN 50629	444704122473001	344		
09S/01W-15DCB03	LINN 51763	444704122472801	145.5	160	-0.38
		CRB/CRB (downward)			
01N/02W-03AAD01	WASH 5090	453613122542901	216		
01N/02W-03ABA	WASH 14	453618122544701	10	1,350	-0.02
02S/02W-34ADB	WASH 13210	452119122544001	683		
02S/02W-34ACD	WASH 3443	452118122545001	511.5	600	-1.44
07S/03W-18BAD01	POLK 1781	445804123061201	330.5		
07S/03W-18AB1	POLK 841	445808123055601	133	1,400	-1.75
08S/02W-13BAD01	MARI 10176	445244122523701	371.5		
08S/02W-12CDB01	MARI 9917	445306122524501	302	2,200	-0.32
		CRB/CRB (upward)			
02S/01W-04ACC	WASH 11449	452534122485101	87.5		
02S/01W-04BAD	WASH 11436	452551122485801	-264	1,600	0.05

the Willamette Basin. This relation can be seen by comparing the head maps for the sediments (pl. 1) and the basalt unit (fig. 19) and by comparing adjacent pairs of wells completed in the two units (fig. 21, table 7). Upward components of flow between these units are probably limited to narrow zones in the lower elevation portions of the floodplains of the Willamette, Clackamas, Tualatin, and Columbia Rivers. Flowing basalt wells in the Tualatin and Portland Basins are generally limited to these low-lying areas (Woodward and others, 1998). Although few wells are open to the basalt unit along most stretches of the Willamette River in the central Willamette Basin, a flowing well near Wilsonville (03S/01W-24BAA01, pl. 1) indicates an upward component of flow in a narrow zone adjacent to the Willamette River in that area.

The vertical component of ground-water flow within the Columbia River basalt unit is downward throughout most of its extent in the Willamette Basin (fig. 21, table 7; Woodward and others, 1998). Upward flow in the Columbia River basalt unit is inferred from upward gradients in two wells in the Tualatin Basin and the occurrence of flowing wells (Woodward and others, 1998). Evidence of upward gradients in the central Willamette Basin is limited to a flowing well near the Willamette River (03S/01W-24-BAA01). Studies in the Willamette Basin and elsewhere (Woodward and others, 1998) suggest that enhanced upward flow and discharge may occur along major faults or sharp folds in the basalt in cases where these structural features enhance vertical permeability.

The low vertical permeability of the basalt flow interiors produces a resistance to vertical flow that can cause substantial head differences between permeable zones, such as a 340 ft head difference between 07S/03W-18BAD01 and 07S/03W-18AB1, and a 250 ft head difference between 02S/02W-34ADB and 02S/02W-34ACD. These well pairs have large downward hydraulic gradients of -1.8 and -1.4 ft/ft respectively. Large head differences are common in adjacent wells in upland outcrop areas and heads in these areas typically decrease with depth (Hampton, 1972; Price, 1967b; Foxworthy, 1970; Miller and others, 1994). Vertical head changes of 25 to 50 ft in the basalt unit over a depth interval of 100 to 200 ft are not uncommon in the uplands. An example of a 141-ft head change over a 243-ft depth interval on the northeast flank of the Stayton Basin is documented by Woodward and others (1998). Vertical head changes of up to 400 ft over a similar depth interval occur in the uplands south of Silverton.

Fluctuations in Ground-Water Levels

Water levels in aquifers reflect a dynamic balance between ground-water recharge, storage, and discharge. If recharge exceeds discharge, the volume of water in storage will increase and water levels will rise; if discharge exceeds recharge, the volume of water in storage will decrease and water levels will fall. Because recharge and discharge are not distributed uniformly in space and time, ground-water levels are continuously rising or falling to adjust to the resulting imbalances. Water levels in wells reflect these changes and provide the principal means of tracking changes in ground-water storage over time. Water-level measurements also provide insight into the physical properties that control aquifer recharge, storage, and discharge since these factors affect the timing and intensity of responses to hydrologic stresses such as precipitation or pumping.

Water levels in the Willamette Basin generally follow a cyclic pattern that mimics seasonal variations in recharge and discharge. High water levels occur in the rainy season when recharge from precipitation exceeds discharge; low water levels occur during the dry summer when discharge by pumping, evapotranspiration, and leakage to streams exceeds recharge. The principal factors that affect ground-water levels are precipitation, stream stage, and well pumpage and injection.

Response to Precipitation

Many wells in the Willamette Basin show a direct, rapid response to short-term precipitation events such as winter storms. This is not unexpected because ground water commonly occurs at shallow depths and average annual precipitation typically exceeds 40 in throughout the basin. In contrast, other wells in the basin show a gradual, or indirect, response to seasonal precipitation. In both cases, the rise in water levels in fall is steeper than the decline in water levels in spring.

The hydrograph for well 16S/05W-26AAD near Eugene in the southern Willamette Basin shows a typical direct response to precipitation (fig. 22, pl. 1). A steep seasonal water-level rise occurs in late autumn or early winter, shortly after the beginning of the annual rainy season, followed by discrete peaks that correlate to periodic storms during the rainy season. Seasonal high water levels occur as multiple peaks or as a broad high that coincides with extended periods of rainfall. Water levels begin to drop in late spring as rainfall diminishes, and continue to fall during the dry summer. The response to rainfall at the beginning of the rainy season is generally delayed by several days or weeks, reflecting the time necessary to bring soil moisture to field capacity (Piper, 1942; Woodward and others, 1998). Once soils are at capacity, however, the effects of additional rainfall occur with little or no delay. Annual high water levels are generally constant from year to year and are within 1 ft of land surface except in exceptionally dry years such as the winter of 2000–01, when annual precipitation was about 50 percent less than average. This suggests that mean annual precipitation is more than sufficient to recharge the aquifer to its maximum capacity in most years.

Wells that show a direct response to precipitation in the Willamette Basin generally tap unconfined or poorly confined aquifers in areas where the water table occurs at shallow depths. These conditions are common in the upper sedimentary unit throughout most of the basin and in shallow parts of the middle sedimentary unit in the southern Willamette Basin,

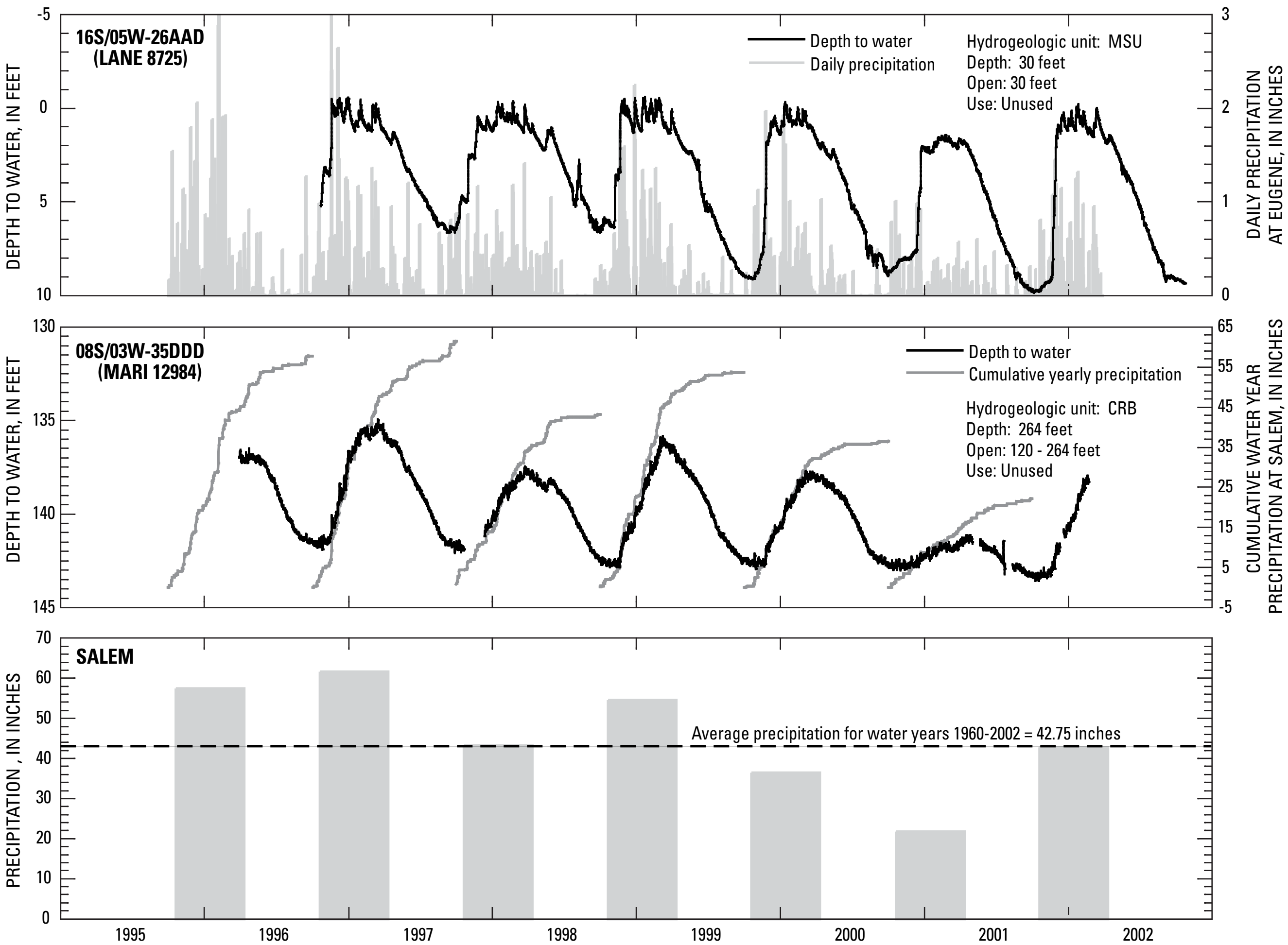


Figure 22. Precipitation and ground-water levels, Willamette Basin, Oregon.

where the overlying Willamette silt unit is relatively thin. Similar responses occur in shallow water-bearing zones of the Columbia River basalt and basement confining units in upland areas where these units are exposed at land surface. Piper (1942) noted a similar response in shallow wells completed in the Willamette silt unit (his semiperched, water-table aquifer) in the central Willamette Basin. The rapid response to precipitation and the direct correlation to individual storms indicate that recharge is local, infiltration rates are rapid, and recharge paths are short.

An example of an indirect response to precipitation is shown by the hydrograph of water levels for 08S/03W-35DDD (fig. 22), a well located south of Salem (pl. 1) and open to the Columbia River basalt unit. Water levels begin to rise shortly after the start of the annual rainy season and follow a trend that is proportional to cumulative seasonal precipitation. Rising ground-water levels correspond to steep increases in the cumulative seasonal precipitation. Annual water levels generally peak and begin to decline in March, when the slope of the cumulative precipitation curve decreases, which is equivalent to a decline in the rate of precipitation. Responses to individual storms are subdued or absent. The highest seasonal water levels generally occur as well-defined peaks that typically coincide with the peak intensity of rainfall during the rainy season. The relative height of seasonal water-level peaks shows a general correlation to annual precipitation. Because seasonal water-level peaks are more than 100 ft below land surface, water levels are free to rise or fall in response to climatic trends. An indirect response to precipitation suggests that infiltration rates are slower or recharge paths are longer relative to wells that show direct responses to precipitation.

Indirect responses to precipitation are common throughout the Willamette Basin in wells that tap unconfined water-bearing zones with deep water tables (generally greater than 40 ft) and in confined water-bearing zones. Examples include wells completed in the confined middle sedimentary unit in the central Willamette Basin and wells completed in the lower part of the middle sedimentary unit in the Portland and southern Willamette Basins. In some wells, high seasonal water levels occur several weeks to several months after the peak of the rainy season.

Response to Stream Stage

As noted by Piper (1942), water levels in wells adjacent to large streams in the Willamette Basin commonly show a close correlation to stream stage. This behavior is illustrated by water levels in a shallow well (11S/05W-35DDD) completed in floodplain gravels of the upper sedimentary unit, about 1,000 ft east of the Willamette River near Corvallis (fig. 23). At most times, water levels in the well are slightly higher than the river stage, indicating discharge from the aquifer to the river. At high river stage, however, the gradient is commonly reversed, indicating flow into the aquifer from the river. Most reversals occur during intense rainstorms and persist for short periods of time only. However, because little resistance to flow is expected between large streams and permeable sediments of the upper sedimentary unit, surface water should readily infiltrate into the adjacent aquifer in reaches near the river when gradients are reversed. Studies by Hinkle and others (2001) and Fernald and others (2001) show that local changes in gradient can cause substantial exchanges between large streams and adjacent floodplain aquifers in the Willamette Basin.

Response to Pumping

Pumping from wells causes water levels to decline in areas surrounding the well. The magnitude of the decline varies with distance and is dependent upon the pumping rate, pumping duration, and the geometry and hydraulic properties of the aquifer. These interference effects are reflected in the water levels of nearby wells. The interference from multiple pumping wells is additive.

Sustained, or seasonal, pumping impacts are common in many wells in the Willamette Basin. Unlike the response of water levels to precipitation only, water levels affected by pumping decline steeply in the summer followed by a broad recovery curve that rises throughout the winter and spring (fig. 24). The recovery from pumping begins at the end of the irrigation season, prior to the beginning of the rainy season. Because the shape of the water-level graph and the timing of response differs from the shape and response of water levels to precipitation (fig. 22), these characteristics may be used as a tool to determine if the summer drawdown is a result of natural changes in recharge or the result of a combination of natural changes in recharge and pumping. Seasonal pumping impacts are common in the Columbia River basalt unit and in confined water-bearing zones of the basin-fill sediments in areas where irrigation or public supply wells are in use, such as in the central Willamette Basin.

The hydrographs for 02N/03W-35CDD and 07S/01W-02CAA01 (fig. 24) show seasonal pumping impacts in wells completed in the Columbia River basalt unit. In 07S/01W-02CAA01, the seasonal drawdown consistently begins before water levels have recovered to the levels of prior years, resulting in a steady, progressive decline of about 5 ft/yr. This is probably caused by consistent annual pumping withdrawals in the surrounding area. The hydrograph for 02N/03W-35CDD

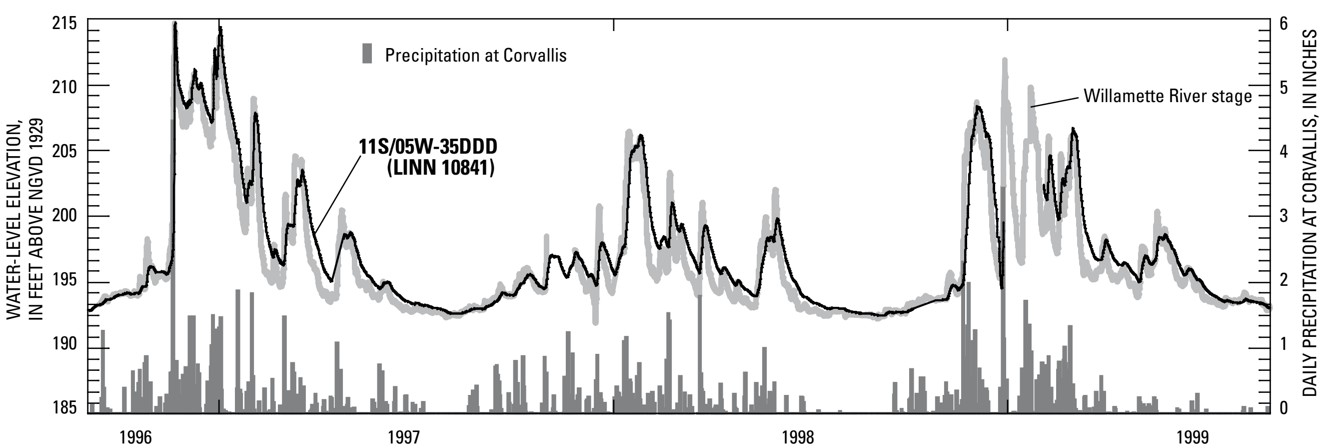


Figure 23. Stream stage, precipitation, and water levels in a shallow well near the Willamette River at Corvallis, Oregon.

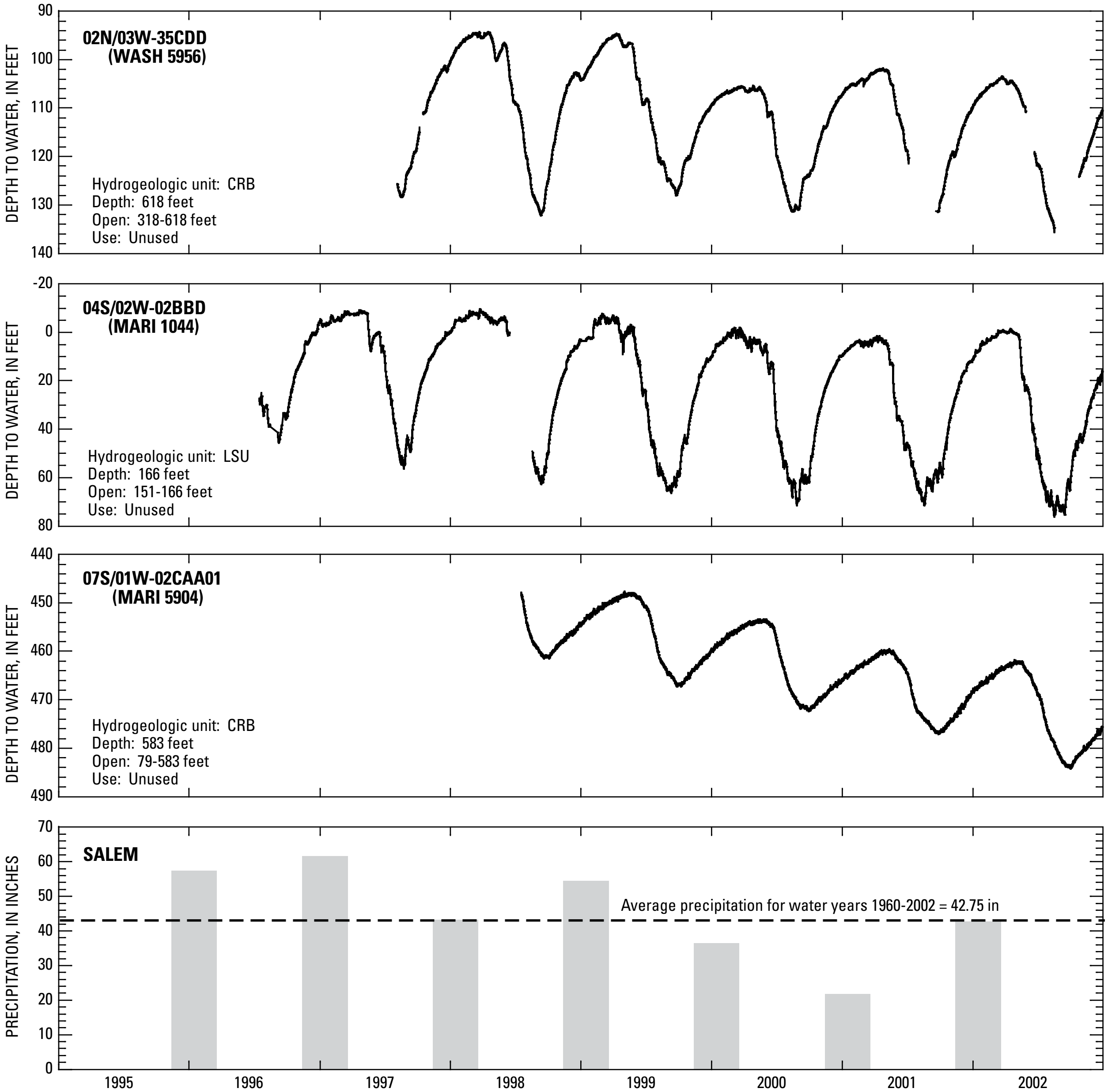


Figure 24. Response of ground-water levels in selected wells to nearby seasonal pumping, Willamette Basin, Oregon. LSU, lower sedimentary unit, CRB, Columbia River basalt unit.

shows no systematic annual trends and no correlation to annual precipitation. Water-level trends in this well probably reflect varying annual pumping withdrawals in the area. The hydrograph for 04S/02W-02BBD, completed in the lower sedimentary unit in the central Willamette Basin, shows a seasonal decline of about 65 ft. A comparison to the 10 ft of seasonal fluctuation in the central Willamette Basin prior to development reported by Piper (1942) suggests that ground-water withdrawals in the area contribute approximately 55 ft of additional seasonal fluctuation. Water levels in this well, located close to the Willamette River, do not respond to changes in stream stage, indicating that the fine-grained material above the completion interval provides a poor hydraulic connection to the stream.

Response to Injection

Several municipal water utilities, including the Cities of Portland, Tigard, Tualatin, Beaverton, and Salem as well as the Tualatin Valley and Clackamas Water Districts are developing aquifer storage and recovery projects. These projects are designed to inject surface water into aquifers during the winter when demand is low and withdraw it in the summer when demand is high. All of the projects will inject water into the

Columbia River basalt unit, except for the City of Portland, which plans to inject water into the lower sedimentary unit.

Injection and pumping will cause local transient changes in the ground-water systems in nearby areas. This is illustrated in the hydrograph for 01S/01W-33CBC (fig. 25), a well completed in the lower sedimentary unit. The well is located about 3 miles south of a City of Beaverton injection well that is completed in the Columbia River basalt unit. Anomalous water-level rises in the hydrograph correspond to yearly injections in the basalt well that began in 1999. Water levels rose within a few hours after the beginning of the injection and declined shortly after injections stopped. Fluctuations caused by these injections ranged from 4 to 28 ft and were proportional to the volume of injected water. The response of water levels in this well indicates there is a good hydraulic connection between the Columbia River basalt unit and the lower sedimentary unit.

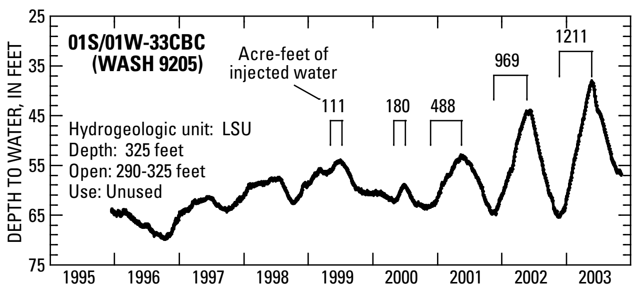


Figure 25. Response of ground-water levels to nearby injection of water, Tualatin Basin, Oregon. LSU, lower sedimentary unit.

Long-Term Water-Level Variability

Long-term water-level variability can be used to determine the natural range of climate-induced water-level fluctuations and to assess the long-term impacts of artificial stresses such as pumping. Under natural conditions, prior to development, ground-water levels are in a state of dynamic equilibrium that reflects a balance between recharge and discharge. Because natural recharge is always variable, water levels will rise and fall in response to multiyear trends of above or below normal precipitation. Over long periods of time, however, water levels will fluctuate around an average value that reflects the long-term balance between recharge and discharge.

Pumpage from wells is an additional discharge that disrupts this natural balance (Theis, 1940; Alley and others, 1999; Bredehoeft, 2002; Sophocleous, 2002). As a well is pumped, ground water is removed from storage in the vicinity of the well, causing water levels to decline in the surrounding aquifer. As pumping continues, the region of lowered water levels forms a cone of depression that expands outward from the pumped well until it captures natural discharge, or induces additional recharge, that is equal to the pumping rate. A capture of natural discharge, for example, occurs when the cone of depression of a pumping well lowers the horizontal hydraulic gradient (water-table slope) adjacent to a stream and captures ground water that would normally discharge into the stream. If pumpage cannot be offset by captured discharge or induced recharge, water will continue to be removed from storage in the aquifer and water levels will decline over time.

An example of the effect of long-term climatic variability on ground-water levels is illustrated by the hydrograph for well 06S/02W-17DAD, several miles northeast of Salem (fig. 26). The well is 120 ft deep and is completed in the middle sedimentary unit, which is confined by about 60 ft of saturated Willamette silt unit. Seasonal high water levels in the well show a general correlation to precipitation trends. Rising water-level trends correspond to periods of above average precipitation and declining water-level trends correspond to periods of lower than average precipitation.

These trends are particularly evident for a 10-year period of below average precipitation between 1984 and 1994 and a subsequent 5-year period of above average precipitation from 1994 to 1999. Although year-to-year changes in seasonal high water levels are generally less than 2 ft and small compared to seasonal fluctuations, cumulative changes over periods of above or below average precipitation range up to 10 ft. The largest year-to-year water-level changes, drops of about 8 ft, occurred during the drought years of 1977 and 2001, when precipitation was almost 50 percent less than normal. Approximately 80 percent of this water-level drop was recovered in the next wet season, which, in both cases, experienced about average amounts of precipitation. A general water-level decline of about 7 ft over the 40-year period of record suggests that some long-term decrease in storage is occurring that cannot be attributed solely to climatic cycles. This long term decline is probably caused by ground-water withdrawals, which have increased considerably since the early 1960s in the central Willamette Basin.

Climatic trends in most long-term observation wells in the Willamette Basin are rarely more pronounced than in the above example. In many cases, annual high water levels are consistent from year to year except during drought years such as 1977 and 2001. In these wells, climatic trends are absent because many shallow long-term observation wells are completed in shallow basin-fill sediments where the water table is near land surface, placing an upper limit on water levels, and therefore, on the available storage. In most years, precipitation appears to be sufficient to fully recharge the shallow aquifer system in most of these areas. Water levels in observation wells in upland areas commonly correlate to climatic trends (e.g., 08S/03W-35DDD in fig. 22) because the water levels are generally deeper in these areas, storage is not limited by the proximity of land surface, and, if other hydraulic boundaries are absent, water levels are free to rise and fall in proportion to annual precipitation.

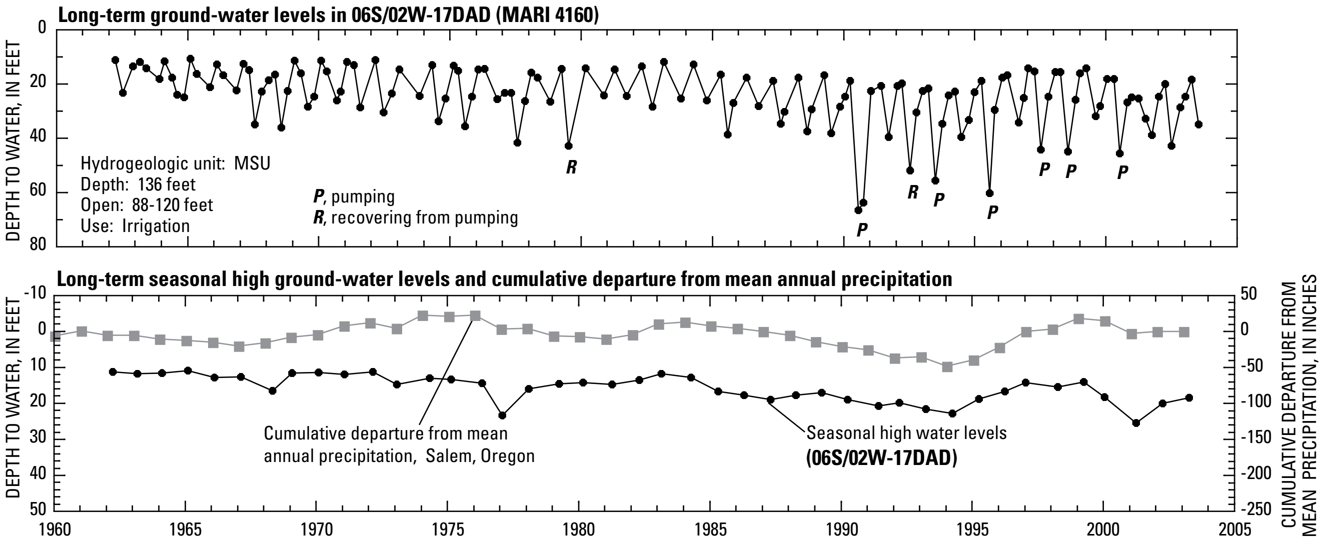


Figure 26. Precipitation and long-term water-level variability in a well near Salem, Oregon.

Climatic trends are commonly masked in wells that show seasonal pumping impacts in the Willamette Basin. Some of the hydrographs in figure 24, for example, show residual trends that are probably related to precipitation but the climatic signal is largely overwhelmed by pumping impacts.

The above examples set a context for evaluating factors that control long-term water-level trends in the Willamette Basin. In the following sections, representative long-term hydrographs are shown for each part of the basin and the major factors that control long-term trends and water supplies are identified.

Southern Willamette Basin

Ground water levels in the basin-fill sediments of the southern Willamette Basin show little variability over the last 50 years. Representative hydrographs (fig. 27) show shallow water levels and consistent seasonal fluctuations that are generally less than 15 ft. Weak climatic trends are evident in 12S/04W-35CDC, completed in the lower sedimentary unit, and 15S/03W-19ACD1, completed in the middle sedimentary unit, but not in 17S/01W-29ACC, completed in the upper sedimentary unit adjacent to the McKenzie River. Lower peak water levels are discernable in some of the wells during the drought years of 1977 and 2001, but long-term changes in water levels are not evident over the period of record. Seasonal fluctuations are essentially unchanged from natural conditions (Piper, 1942), even though about 106,000 acre-ft of ground water are now pumped from the basin-fill sediments in this part of the valley (table 4).

Several factors probably contribute to this long-term stability in shallow wells. Recharge is relatively direct and efficient throughout the area because water levels show a direct response to precipitation, or a close correlation to stream stage, and no seasonal pumping impacts. Recharge is sufficient to fully saturate the aquifer during most winters. Ground-water withdrawals do not result in long-term drawdowns or large seasonal fluctuations because the effects of irrigation withdrawals from the upper sedimentary unit adjacent to the floodplain of the Willamette River are buffered by the stream stage of the Willamette River. Most current pumpage, and any new pumpage, from areas adjacent to the major streams will largely be at the expense of streamflow (Piper, 1942). Depletion of streamflow in the Willamette River from nearby ground-water withdrawals is not measurable because of limited streamflow measurements, flow regulation at upstream reservoirs, and these withdrawals represent a small portion of streamflow.

The Columbia River basalt unit occurs in a limited area in the northern part of the southern Willamette Basin (fig. 10). The overall productive capacity of the basalt unit is limited in this area because the unit is generally less than 500 ft thick and contains only a few interflow zones. These limits are illustrated by the progressive, long-term declines in the hydrograph for 09S/01W-14DCA (fig. 27), which is dominated by the impacts of nearby pumping.

Central Willamette Basin

The principal aquifers within the central Willamette Basin occur in the basin-fill sediments and in the Columbia River basalt unit. Long-term water-level variability for selected wells is shown in figure 28.

Within the floodplains of the Willamette and Molalla Rivers, ground water is unconfined in the upper sedimentary unit. Outside of these areas, the water table occurs near land surface in the Willamette silt unit and ground water is generally confined in the underlying middle sedimentary unit (Piper, 1942). Hydrographs for 04S/01W-05CDC, 05S/02W-01DDA,

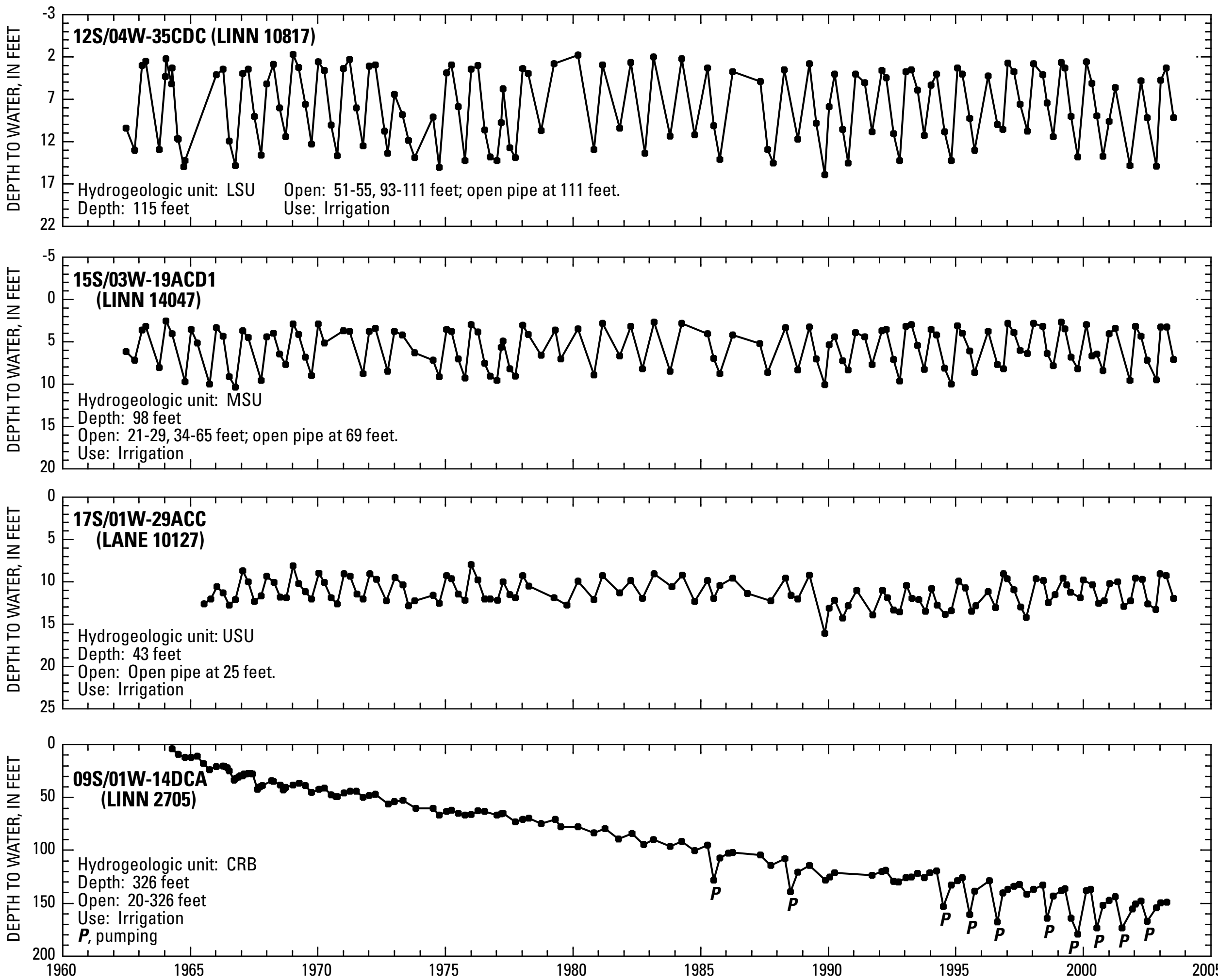


Figure 27. Water levels in selected long-term observation wells in the southern Willamette Basin, Oregon.

and 05S/02W-19DCC show typical trends for wells completed in confined water-bearing zones of the lower sedimentary unit and the middle sedimentary unit in the central Willamette Basin. Seasonal pumping impacts are evident and seasonal water-level fluctuations have increased over time. Climatic trends are not obvious, but the impacts of the 1977 and 2001 droughts are visible. Piper (1942) documented seasonal fluctuations of 8 to 10 ft in the confined aquifers in the area in the early half of the 1900s, prior to extensive development. Ground-water withdrawals have resulted in current fluctuations that range from 20 to 65 ft over a broad area between Wilsonville and Salem (fig. 29). Assuming predevelopment seasonal fluctuations of 10 ft (Piper, 1942), it is estimated that ground-water withdrawals result in 10 to 55 ft of additional seasonal fluctuation. The large fluctuations are caused by pumping from the middle sedimentary unit where the unit is thin, generally less than 20 ft. Seasonal fluctuations generally decrease to the south as the unit thickens. The coherent pattern of seasonal drawdowns (fig. 29) and the broad pattern of irrigation withdrawals (fig. 17) indicate that pumping interferences overlap throughout the area to produce a broad seasonal drawdown rather than a network of isolated drawdowns around individual pumping wells. This is consistent with the behavior of confined aquifers, which tend to propagate pumping effects out to much greater distances than unconfined aquifers.

Although annual withdrawals from the basin-fill sediments are similar in the central and southern Willamette Basins (table 4), the impacts of pumping are considerably larger in the central basin. Most of these differences are due to a broader distribution of withdrawals and widespread occurrence of confined water-bearing zones in the sediments of the central Willamette Basin.

The hydrographs for 04S/01W-05CDC and 05S/02W-01DDA (fig. 28) show subtle long-term water-level declines of 10 ft. The available data are not sufficient to determine whether these declines occur over broad areas or are limited to the vicinity of each well. Both wells are within the area of broad seasonal drawdowns discussed above and both show seasonal fluctuations of at least 40 ft. Well 04S/01W-05CDC

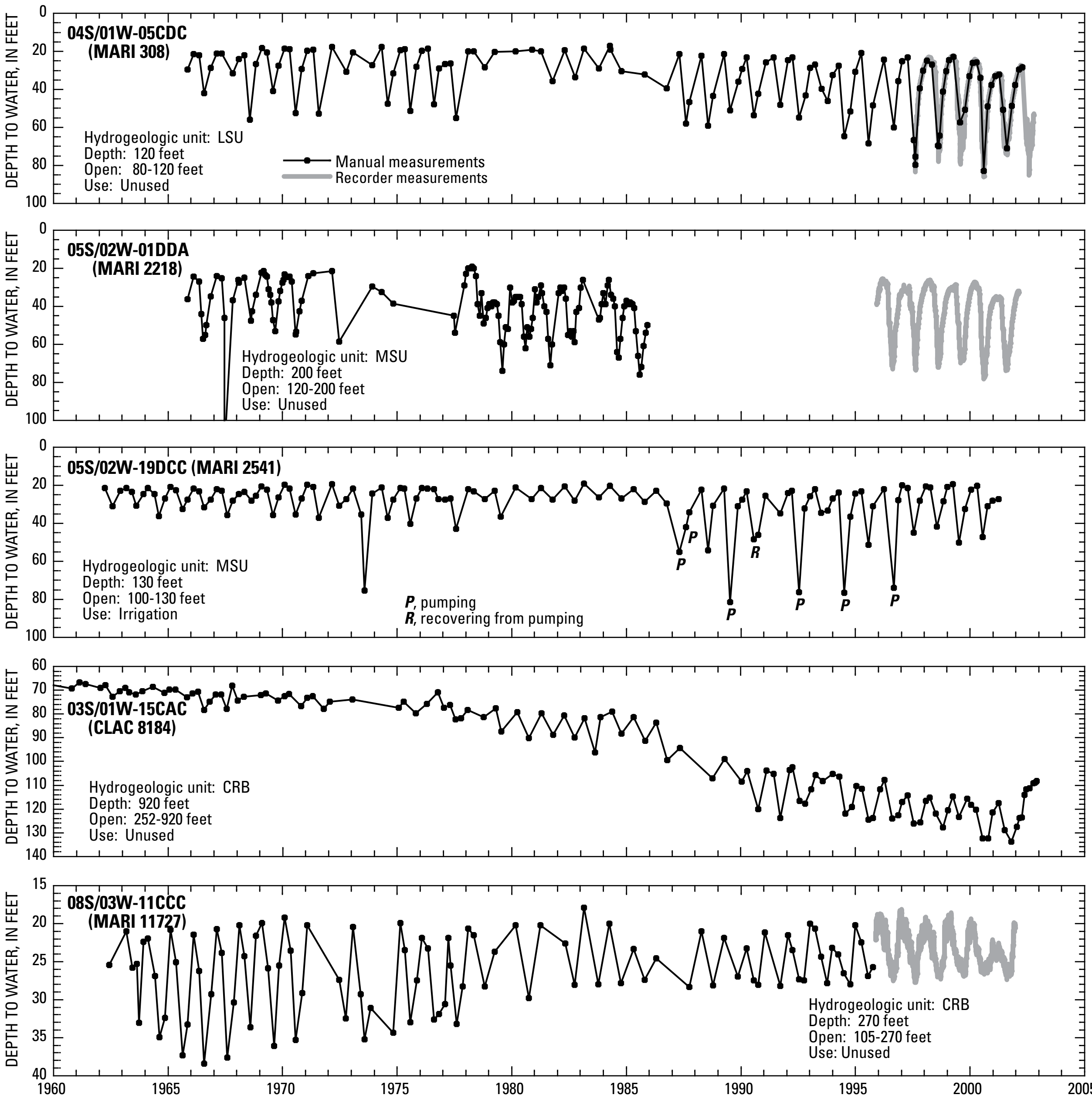


Figure 28. Water levels in selected long-term observation wells in the central Willamette Basin, Oregon.

is open to a thin interval of middle sedimentary unit in an area that is intensely irrigated with ground water. Well 05S/02W-01DDA is located near several municipal wells that supply the city of Woodburn. Smaller long-term water-level declines are evident in other wells in the central Willamette Basin (e.g. 06S/02W-17DAD in figure 26; also see hydrographs in Orzol and others, 2000) but systematic trends are not apparent. The lack of long-term water-level declines in most of the central basin suggests that ground-water withdrawals are compensated each year by a decrease in discharge to streams or by an induced increase in recharge. Because the low-permeability Willamette silt unit underlies smaller streams, ground-water pumpage is probably at the expense of streamflow in large streams that penetrate coarse-grained basin-fill sediments. Additional pumpage in the central Willamette Basin will probably lead to larger seasonal water-level fluctuations over broader areas, especially in areas where the sands and gravels are thin.

Long-term water-level trends in the Columbia River basalt unit are highly variable in the central Willamette Basin.

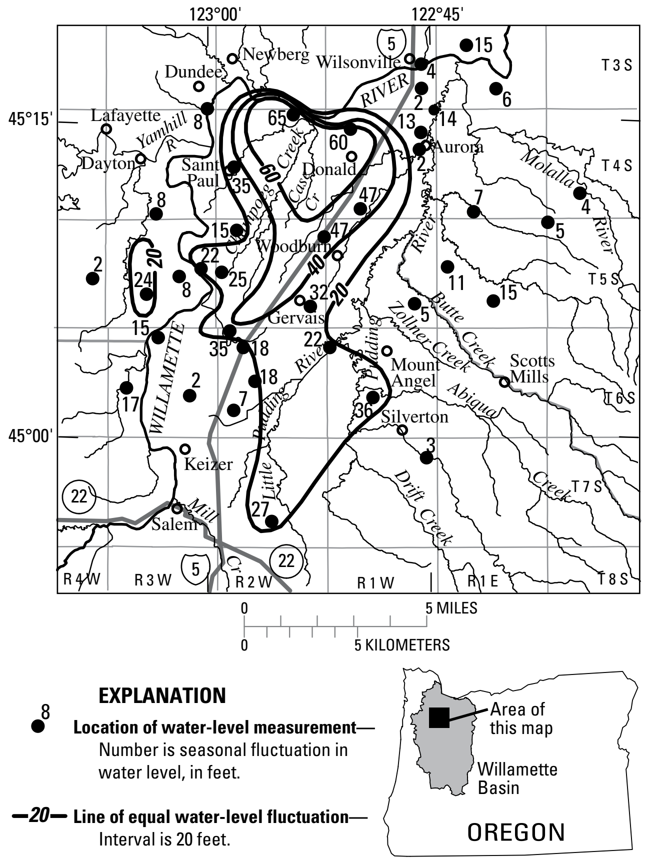


Figure 29. Amplitude of seasonal ground-water fluctuations in basin-fill sediments, 1997–98, central Willamette Basin, Oregon.

The hydrographs for 03S/01W-15CAC and 08S/03W-11CCC (fig. 28) show two contrasting trends that illustrate the impact of nearby pumping withdrawals.

A 920-ft deep well, 03S/01W-15CAC, just west of Wilsonville, shows a water-level decline of about 55 ft between 1960 and 2002. During the same period, seasonal fluctuations increased from 5 to 15 ft/yr. These changes coincide with a period of increased withdrawals from basalt wells that provided water to the City of Wilsonville. By 2002, daily withdrawals from these wells totaled 2.7 million gallons, the equivalent of a continuous pumping rate of about 4.2 ft^3/s (1,900 gal/min (gallons per minute), 3,000 acre-ft/yr). On April 29, 2002, Wilsonville converted to a surface-water source and stopped pumping from its basalt wells. Within 24 hours, water levels in 03S/01W-15CAC began an abrupt rise which continued throughout most of the summer when water levels generally fall in the area. Within a year of the conversion, water levels had risen by 20 ft, the equivalent of about one-third of the total decline of the previous 40 years. Water-level declines and recoveries have been observed in basalt wells as far as 4 miles east and 6 miles south of Wilsonville (fig. 20). These observations indicate that pumping by the city of Wilsonville was the dominant factor controlling long-term water-level declines in the deep Columbia River basalt unit in this area and that pumping impacts occurred at distances of at least 6 miles in some directions. The long-term declines prior to 2002 and the relatively large area of impact despite the small annual withdrawals suggest that the expanding cone of depression was unable to capture natural discharge or induce additional recharge at levels anywhere near the average pumping rate. This suggests that the deep Columbia River basalt unit is not well connected to the overlying sedimentary aquifers or to nearby surface water sources. In fact, pumping impacts occurred up to 5 miles south of the Willamette River even though most of the city of Wilsonville's pumping wells are located on the north side of the river. These observations are not surprising considering that the main mass of the Columbia River basalt unit consists of thick flow interiors with low vertical permeabilities.

Although substantial recovery has occurred during the first year following the cessation of pumping by Wilsonville, complete recovery is likely to take many years, possibly several decades. If additional ground water is withdrawn from the basalt for other uses in the future, recovery will be delayed and possibly reversed.

The long-term hydrograph for 08S/03W-11CCC (fig. 28), a relatively shallow basalt well in the Salem Hills, shows a progressive decrease in seasonal fluctuations between the late 1960s and 2002. Seasonal high water levels have remained relatively constant at about 20 ft below land surface for the period of record, and no progressive trends are evident except a 4-ft drop associated with the 2001 drought. Prior to about 1975, the well was located outside of the Salem city limits in an area of rural subdivisions and farmland that were supplied by domestic and irrigation wells completed in the Columbia River basalt unit. The surrounding area is now within the city of Salem, and withdrawals from the unit in the area are much reduced. This suggests that the decrease in seasonal fluctuations in 08S/03W-11CCC is the result of a decrease in ground-water pumpage over time. The absence of a long-term decline in the well indicates that withdrawals were small compared to the average annual recharge. The direct and rapid response to precipitation, especially visible between 1996 and 2002 when a recording device was installed, suggests that the well is completed in an unconfined aquifer in the basalt. If pumping is no longer occurring in the area, the average seasonal fluctuation of about 8 ft in recent years should represent the average natural seasonal fluctuation in the shallow basalt aquifer.

Tualatin Basin

Most ground-water withdrawals in the Tualatin Basin are from the Columbia River basalt unit. Long-term water-levels in this unit are generally only available for wells in the vicinity of Cooper and Bull Mountains in the southeastern portion of the basin. The hydrograph 01S/02W-23ACB (fig. 30) is typical for many of the deep basalt wells in this area. Water-level declines occurred throughout the 1960s and early 1970s as the unit was developed for public supply and irrigation uses. Water levels recovered throughout most of the late 1970s and 1980s after pumping restrictions were implemented by the

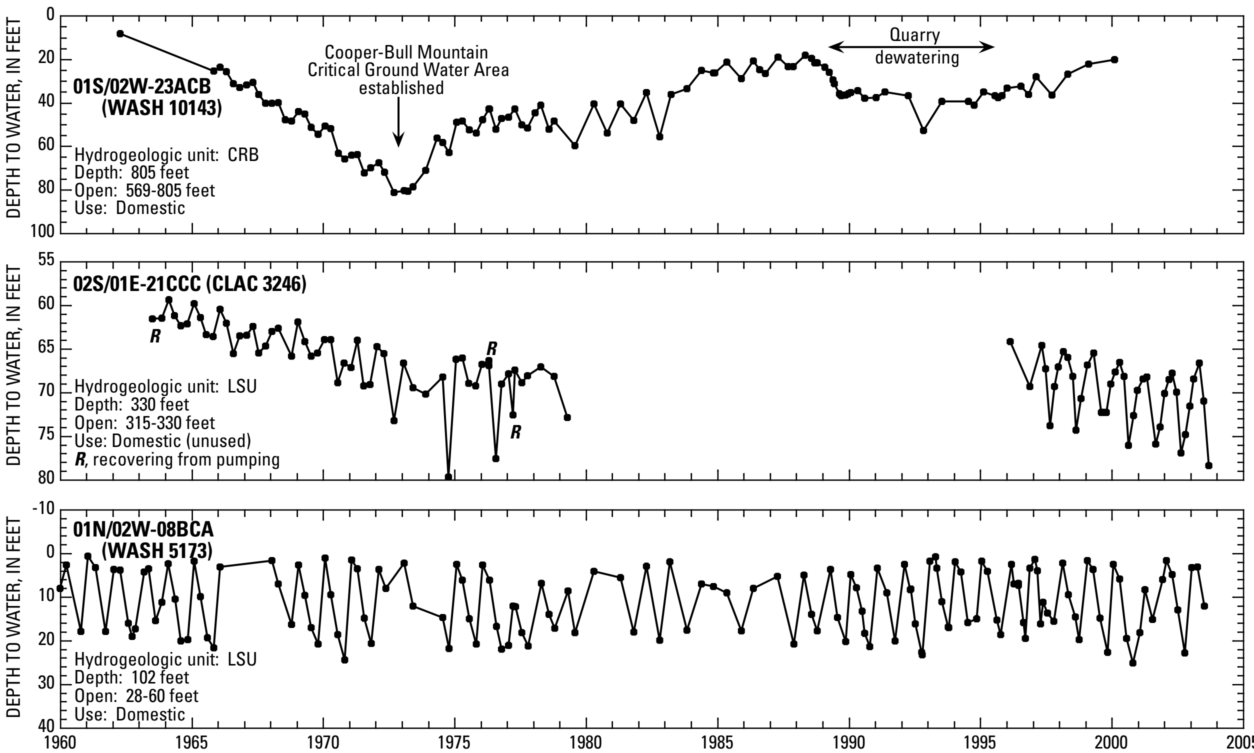


Figure 30. Water levels in selected long-term observation wells in the Tualatin Basin, Oregon.

OWRD. A subsequent decline of about 20 ft in the late 1980s was caused by the dewatering of a quarry in the unit about one-half mile to the south of 01S/02W-23ACB and is localized to the vicinity of the quarry (Marc Norton, OWRD, oral commun., 2003).

The hydrograph for 01N/02W-08BCA (fig. 30) is probably representative of the shallow sediments in the basin. Seasonal fluctuations are typically about 15 ft and show no trends over time. Seasonal high water levels were lower during the 1977 and 2001 droughts and the long-term trend shows a general correlation to climatic trends. In contrast, the hydrograph for well 02S/01E-21CCC (fig. 30), completed in a deeper section of the basin-fill sediments, shows several long-term trends. A decline in the 1960s and early 1970s does not correspond to climatic trends but is roughly coincident with declines in the Columbia River basalt unit near Cooper and Bull Mountains, about 4.5 miles to the northwest. Water levels measured after 1995 show an indirect response to precipitation and a general correlation to annual precipitation. Seasonal high water levels were higher during the wet years of 1996 and 1997 and lowest during the 2001 drought. Declining water levels in the 1960s and early 1970s may have been caused by pumping from the underlying basalt unit, whereas the later trend may represent the natural climatic response of the deep sediments when pumping withdrawals are much lower in the basalt unit. Water levels in this well may not be representative of hydraulic conditions of the deeper part of the lower sedimentary unit in the Tualatin Basin because the well is screened in sediments filling a deep trench in a constricted part of the Tualatin Basin that is not representative of conditions elsewhere in the basin.

Portland Basin

Most ground-water withdrawals in the Portland Basin are from the basin-fill sediments (table 4). Minor amounts are pumped from the Columbia River basalt unit. Long-term hydrographs are available for the sedimentary units but not for the basalt unit.

The hydrograph of 03N/01W-06BAA1 (fig. 31) shows long-term water-level variability that is typical of shallow wells completed in the upper sedimentary unit near major streams in low-lying areas of the Portland Basin. Water-level fluctuations are generally less than 10 ft and seasonal high water levels were lower during the droughts of 1977 and 2001. No long-term changes in storage are evident, but water levels show a general correlation to climatic trends or stream stage. These factors suggest that ground-water withdrawals are buffered by nearby streams in these areas.

An example of long-term water-level variability in basin-fill sediments in upland areas is illustrated by the hydrograph of 02S/04E-29DAD (fig. 31). This is a relatively shallow well completed in a section of the middle sedimentary unit that is isolated on a narrow terrace between two deeply incised creeks. Long-term water-levels show a general correlation to climatic variability.

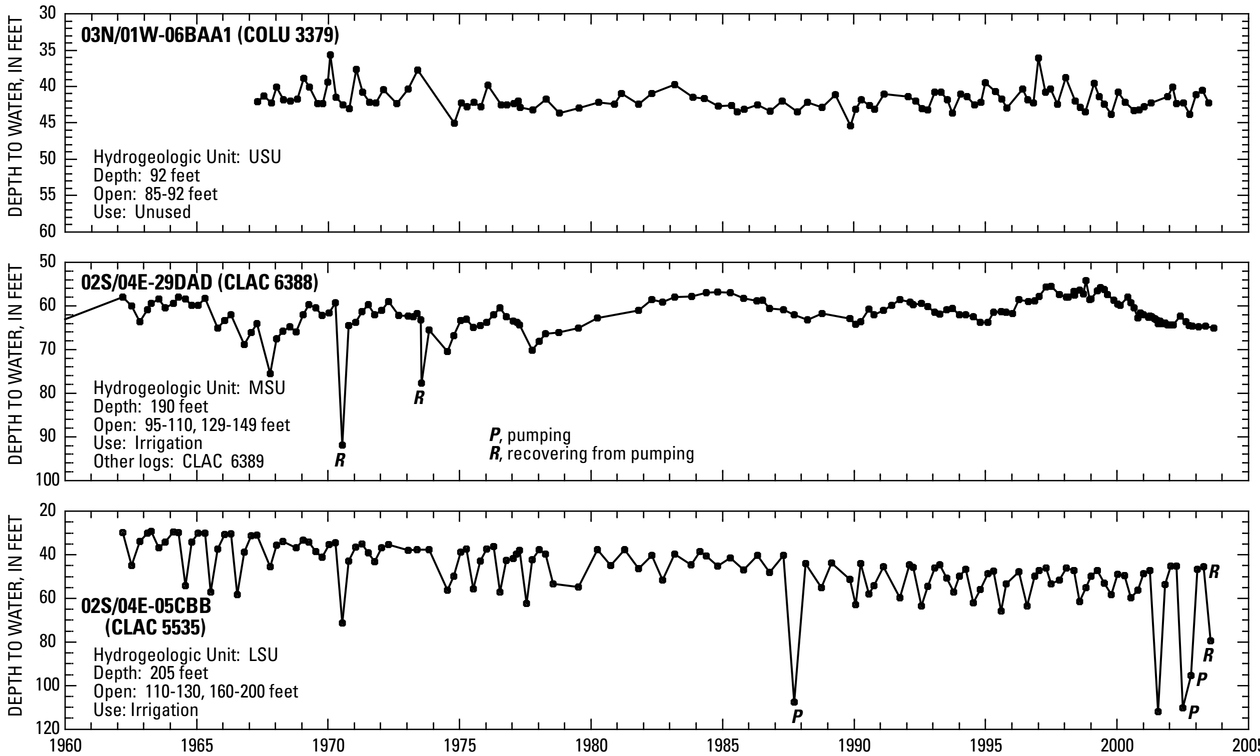


Figure 31. Water levels in selected long-term observation wells in the Portland Basin, Oregon.

Long-term pumping impacts in the basin-fill sediments have been documented in several areas in the southern part of the Portland Basin near the communities of Boring and Damascus. Most affected wells are completed in confined sands and gravels of the middle sedimentary unit or the lower sedimentary unit in areas where pumpage from community supply wells and irrigation wells has increased over time. The extent of declining water levels in these areas is not well documented. A typical example is shown in the hydrograph of 02S/04E-05CBB (fig. 31), which exhibits a slow but progressive decline of approximately 20 ft between 1965 and 2000. Increased pumpage in these areas is likely to lead to more widespread water-level declines.

Changes in Ground-Water Storage from Ground-Water Withdrawals

Changes in ground-water storage are assessed by tracking water-level fluctuations in wells over time. Seasonal changes in storage are caused by variations in seasonal recharge and pumping. Long-term changes in storage are generally caused by multiyear trends of falling or rising precipitation or by increased withdrawals from wells. The following section is limited to a discussion of long-term changes in storage that can be attributed to ground-water withdrawals.

In the basin-fill sediments, average annual ground-water levels have remained remarkably constant over the past 70 years despite the intense development of this resource since 1960. Examples of long-term water-level declines are of limited extent and occur only in the deeper confined portions of the middle sedimentary unit and the lower sedimentary unit. Declines of 20 to 30 ft between 1960 and 2000 (0.5 to 0.8 ft/yr) have been observed near the cities of Damascas and Boring in the Portland Basin (well 02S/04E-05CCB in figure 31). Smaller declines of less than 10 ft (0.2 ft/yr) have occurred since 1970 near Woodburn, Gervais, and Donald in the central Willamette Basin (wells 04S/01W-05CDC and 05S/02W-01DDA in figure 28). Declines are not evident in the southern Willamette Basin.

In contrast to the basin-fill sediments, long-term changes in storage are common in the Columbia River basalt unit. In the basin lowland, declines often occur over broad areas associated with clusters of irrigation or public supply wells that pump from the basalt unit. In upland areas, where the basalt unit is exposed at land surface, declines appear to be more localized. Data collected by OWRD suggests that local declines of 1 to 3 ft/yr may be occurring in parts of the Eola Hills, Parrett Mountain, and at scattered locations in Washington County.

In the central Willamette Basin, water levels in the Columbia River basalt unit are declining over a broad area along the eastern margin of the valley floor extending at least 8 miles northeast and 8 miles southwest of the city of Mount Angel. Extensive development of the basalt unit for irrigation and municipal water supplies has occurred in this area since the early 1990s. Water-level declines are not uniform throughout the area, but patterns of relatively uniform decline occur in several areas. In the area immediately north of the Mount Angel fault, water levels are declining at rates of about 3 ft/year. Farther to the northeast, decline rates vary from 1 to 3 ft/yr. Immediately south of the Mount Angel fault, water levels are declining at rates of 5 to 6 ft/yr (07S/01W-02CAA01, fig. 24). Farther south of Mount Angel, decline rates are generally less than 3 ft/yr. Less areally extensive areas of decline are occurring in the basalt unit south of Stayton, Oregon, where water levels have declined 4 ft/yr since 1964 (fig. 27).

Historic declines of many tens of feet have occurred in the area around the City of Wilsonville (fig. 20) and also in the area around Cooper and Bull Mountains, west of the Cities of Beaverton and Tigard (fig. 30). Water levels in the Cooper-Bull Mountains area, which were declining at a rate of 1 to 8 ft/yr between the early 1960's and 1974, have recovered to within about 90 percent of their predevelopment levels since controls on pumping were established by OWRD in 1976. Water levels, which declined over 1 ft/yr, have been rising in the Wilsonville area since late April of 2002 when the City of Wilsonville stopped pumping from its basalt wells (fig. 28).

Although ground-water withdrawals from the Columbia River basalt unit represent only 11 percent of total withdrawals in the Willamette Basin, most instances of declining water-levels attributable to pumping occur within this unit. Modest rates of withdrawal, such as 2.7 million gallons per year (equivalent to 1,900 gal/min or 3,000 acre-ft/yr) withdrawn by the City of Wilsonville, can lead to substantial ground-water declines over time. This suggests that some unique features of the basalt unit control its sensitivity to pumping stresses.

A limited ability to store water is a contributing factor. Interconnected pore space is largely limited to tabular interflow zones, which generally account for less than 10 percent of the total thickness of basalt unit. Because the porosity of these zones is probably less than 25 percent, ground water probably occupies less than 2.5 percent of the bulk volume of the unit. Related to porosity is the storage coefficient of the confined unit, which is quite low, 0.0001, calculated from aquifer tests. The limited ability to store water causes the cone of depression of a pumping well to extend out to considerable distances in order to capture the water that is removed by the well.

The storage coefficient of the basalt unit is similar to that of the confined middle and lower sedimentary units. Yet annual pumpage of about 104,000 acre-ft from the middle and lower sedimentary units in the central basin has not induced widespread water-level declines, whereas annual pumpage of about 19,000 acre-ft from the basalts has caused widespread declines. This suggests that the basalt unit does not capture natural discharge or induce additional recharge as efficiently as the confined middle sedimentary unit.

The basalt unit has no direct connection to major streams in the basin to capture natural discharge, unlike the middle sedimentary unit, which has an efficient connection to the major streams through the adjacent upper sedimentary unit. Its ability to capture additional recharge is less than for the middle sedimentary unit because the layers of low permeability flow interiors inhibit infiltration of precipitation and downward flow of ground water from overlying hydrogeologic units. The middle sedimentary unit is overlain by a considerable thickness of saturated Willamette silt unit of high bulk porosity. These saturated fine-grained materials contain a considerable volume of water that can be released to adjacent coarse-grained sediments when water is pumped from the latter. These factors suggest that the susceptibility of the Columbia River basalt unit to pumping-induced water-level declines is largely controlled by features of the physical geometry of the basalt lava flows that limit the influx of water into the unit.

Suggestions for Future Study

Understanding the hydrology of the Willamette Basin is complicated by many factors: surface-water flows are managed, flow rates between surface and ground water are difficult to measure, irrigation water use is not generally reported, precipitation varies widely across the basin, well data are scarce in large portions of the Coast and Cascade Ranges, and ground-water flow within the Columbia River basalt unit is poorly understood. This study has provided information about the interaction of surface and ground waters, estimation of water use, geometry of the Columbia River basalt unit, spatial distribution of recharge, ground-water flow patterns, and variability in ground-water levels.

The scope of this study did not allow a complete understanding of all aspects of the ground-water hydrology of the Willamette Basin. For example, ground-water flow within the Columbia River basalt unit is believed to be largely controlled by permeable interflow zones and less permeable flow interiors; yet most studies, including this one, do not delineate the permeable and less permeable zones in the unit because interflow zones and their hydraulic connection laterally and vertically have not been identified. Identification of interflow zones and the hydraulic connection laterally and vertically between interflow zones should be assessed in future studies. Drilling test wells and collecting water-level measurements, geophysical logs, and well test data in wells open to the Columbia River basalt unit will provide insight into the permeability of interflow zones and the connection between interflow zones. Packer tests and downhole flowmeter logs can quantify the permeability and contribution of individual interflow zones.

Recharge to and discharge from the Columbia River basalt unit are assumed to be small, yet are uncertain. Possible recharge mechanisms include infiltration of precipitation in areas where the unit crops out, downward flow of ground water from basin-fill sediments into the unit, and seepage of surface water where streams are incised into the unit. The mechanism and rate of flow downward and upward through the fine-grained laterite and the low permeability flow interiors are unknown. Regionally, discharge is assumed to be from upward flow through basin-fill sediments to the Tualatin River in the Tualatin Basin, the Willamette River in the central

Willamette Basin, and the Willamette, Clackamas, and Columbia Rivers in the Portland Basin but has not been quantified.

The large vertical gradients where the Columbia River basalt unit crops out suggests that the role of flow interiors as confining units may be important, and subdividing the Columbia River basalt unit into multiple aquifers and confining units is necessary to better define and simulate flow in the unit. Stratigraphic mapping and correlating the basalt stratigraphy to hydrogeologic units would facilitate this effort.

Ground water within the lowland discharges to streams. The magnitude of this discharge was estimated as the residual of a water budget because the measured ground-water discharge to streams was often within the uncertainty of the measurement. More detailed studies may improve the quantification and location of ground-water discharge to streams. As discussed above, future measurements should be made in areas where focused discharge of ground water to major streams is expected, such as where the Willamette and Santiam Rivers flow through gaps in the basement confining unit near Albany. It will be important to obtain accurate measurements of seepage to and from streams in order to determine the effect pumping has on streamflows.

Saline water, often identified by high concentrations of chloride in ground-water, is found in some wells open to the basement confining unit and the Columbia River basalt unit. A component of this saline water represents connate water, ancient sea water that was trapped in the marine sediment deposited when the present-day Willamette Basin was covered by an ancient sea. Concentrations of chloride in ground water that are greater than that expected in connate water suggest that sources and processes have further modified the concentration of chloride in ground water. Further study could identify the sources and processes that result in high concentrations of chloride in ground water. These studies would aid prediction of areas where wells may encounter saline water or where pumping from wells may induce flow of saline water to a freshwater aquifer.

If faults create a barrier to horizontal flow in the basalt unit, they will probably have a large impact on the dynamics of ground-water flow when the unit is stressed by pumping since the propagation of pumping impacts will be limited across these boundaries. Location or drilling of wells open to similar interflow zones on opposite sides of mapped faults is necessary to evaluate the effect of faults on water levels and ground-water flow.

Summary and Conclusions

Ground-water flow in the Willamette Basin is controlled by geology, recharge from precipitation, withdrawals, and stream stage. The age, texture, type, and distribution of rocks and sediments affect the quality and quantity of water produced from the subsurface. These rocks and sediments were grouped into seven hydrogeologic units based on their hydrologic properties. Limited to the High Cascade area along the eastern edge of the basin, the High Cascade unit consists of young, permeable volcanic material. Precipitation can easily infiltrate into this unit, and both thermal and nonthermal springs sustain relatively stable streamflows throughout the year. Few wells are drilled in this remote, largely uninhabited area. In the lowland, rock and unconsolidated deposits provide ground water for major users. The upper sedimentary unit consists of thin, very permeable sands and gravels generally found at land surface in the floodplains of the major streams and in the Portland Basin. Covering much of the lowland and occurring at the land surface, the Willamette silt unit consists of silts and clays of low permeability. Beneath the Willamette silt unit and upper sedimentary unit, and at land surface as terrace deposits, the middle sedimentary unit is a permeable unit consisting of widespread semiconsolidated sands and gravels in alluvial fans and braided stream deposits. Underlying the upper and middle sedimentary units is the lower sedimentary unit consisting of fine-grained less permeable deposits. In general, the lower sedimentary unit is a confining unit, but in places, most notably in the Portland Basin and parts of the central Willamette Basin, the unit contains coarse-grained deposits that are productive aquifers. The Columbia River basalt unit, a series of flood basalt flows that were subsequently deformed, is present in the northern part of the lowland beneath sedimentary units and in the upland hills at land surface. Ground water is produced from interflow zones consisting of vesicular and brecciated basalt flow tops and bottoms.

Older altered volcanic and marine deposits of the low permeability basement confining unit define the bottom of the ground-water flow system. Where the unit is present at the surface, in the Western Cascade area and Coast Range, well yields are sufficient only for domestic use and where marine sediments are encountered high salinity water may be produced.

The upper and middle sedimentary and Columbia River basalt units are the major aquifers in the central Willamette and Portland Basins. The upper and middle sedimentary units are the major aquifers in the southern Willamette Basin and the Columbia River basalt unit is the major aquifer in the Tualatin Basin.

Most precipitation in the Willamette Basin falls from November to April, with very little precipitation during summer. Precipitation is greatest in the mountain ranges and generally decreases with elevation. The distribution of recharge mimics the distribution of precipitation. Recharge, simulated with watershed models, is greatest in the high altitude area in the Coast Range and Western and High Cascade areas, where the orographic effect results in large amounts of precipitation. Within these high precipitation areas, recharge is expected to be greater in the High Cascade area, where precipitation easily infiltrates into the young, permeable rocks of the High Cascade unit. In the Coast Range and Western Cascade area, recharge is less because the less permeable rocks of the basement confining unit and the deeply incised streams favor runoff over infiltration. Simulated recharge is least in the lowland where precipitation is least; however, ponding of water over large areas in the lowland probably enhances recharge. Temporally, recharge is greatest in the winter during the rainy months and negligible in the summer, when precipitation is small and evapotranspiration is high. Mean annual recharge for the basin is 22 in/yr. In the lowland, where water demand is the highest, mean annual recharge is 16 in/yr.

Downward hydraulic gradients indicate that recharge to the shallow ground-water system occurs throughout the lowland. Shallow ground water flows from topographically high areas and discharges to streams where upward gradients are observed. The direction of flow and elevations of water levels in the shallow system have changed little when compared to water-table maps from 1935.

Ground water discharges to streams throughout the year. In the lowland, ground-water discharge is a small component of total streamflow based on seepage runs. For smaller lowland streams that are underlain by the Willamette silt unit, slow drainage of ground water from the Willamette silt unit probably contributes to streamflow, but this flow is diffuse or insignificant relative to total streamflow. Most ground water in the lowland discharges to the Willamette River and its major tributaries, which have a good hydraulic connection to the upper and middle sedimentary units.

Ground-water withdrawals for irrigation, public, and industrial supply were estimated in the Willamette Basin. Approximately 300,000 acre-ft/yr, equivalent to a constant rate of 400 ft^3/s, is pumped from the hydrogeologic units mainly in the lowland. This annual rate of pumping represents 10 percent of average annual recharge in the lowland or 1 percent of average annual flow of the Willamette River at Portland.

Pumping for irrigation, which occurs from May to October, accounts for 81 percent of annual ground-water withdrawals. Most ground water is withdrawn from the upper and middle sedimentary units in the central Willamette Basin and southern Willamette Basin. Lesser amounts are withdrawn from the sand and gravel lenses in the lower sedimentary and Columbia River basalt units in the central Willamette Basin. Approximately 3 percent of ground-water withdrawals in the basin is from the basement confining unit.

Monthly pumping was estimated in the central Willamette Basin. Approximately 1,000 acre-ft per month is withdrawn in winter, mostly for public supply use. Ground-water withdrawals increase to 42,000 acre-ft in July when irrigation demand rises.

Ground-water withdrawals by wells remove ground water from storage in the aquifer or capture ground water that would otherwise discharge to streams. In the lowland, the effect of pumping from the middle sedimentary unit on flow in smaller streams underlain by the Willamette silt unit is small because these streams have a poor hydraulic connection with the aquifer. Ground-water withdrawals from the upper and middle sedimentary units capture water that would otherwise discharge to the Willamette River and its major tributaries, which have a good hydraulic connection to these units.

Ground-water levels in the basin-fill sediments generally do not show long-term declines from ground-water withdrawals. Seasonally, water levels naturally decline in summer as precipitation tapers off. Without pumping, natural seasonal fluctuations in water levels are generally less than 10 ft. Seasonal fluctuations continue to be less than 20 ft in the southern Willamette Basin, where the upper sedimentary unit is close to land surface and pumping occurs close to the Willamette River, which buffers the effect of pumping on water levels. Withdrawal of ground water results in seasonal water-level fluctuations of up to 65 ft in the central Willamette Basin, where pumping is widely distributed from the confined middle sedimentary unit. With recharge from winter rains, water levels generally return to their seasonal high levels in winter. Continued development of the aquifer will result in increases in the seasonal fluctuations of water levels.

The shape of the graph of water levels with time provides insight into stresses affecting water levels in the basin fill. Water levels in wells affected by pumping exhibit steep spring declines and gradual recoveries that begin before the onset of rains in the fall. Where water levels respond to precipitation and are unaffected by pumping, the hydrograph is characterized by gradual spring declines and rapid fall recoveries after the onset of rains. Response to decadal climate variability is evident for some hydrographs where pumping and seasonal fluctuations do not overwhelm the climate signal.

The Willamette silt unit plays an important role in the ground-water hydrology of the central Willamette Basin. Its relatively large thickness and low permeability confine the middle sedimentary unit in the central Willamette Basin. In this area, the Willamette silt unit hydraulically separates streams from the underlying middle sedimentary unit, and pumping from the unit has little effect on streamflows. The Willamette silt unit stores a great volume of water that probably discharges to streams or recharges the underlying middle sedimentary unit.

Water levels in the Columbia River basalt unit, where concentrated withdrawals occur, show long-term declines. Although the permeable interflow zones of the Columbia River basalt unit are productive initially, in areas where many wells withdraw a large amount of ground water over time, water levels decline up to 6 ft/yr because the unit has low storage properties and receives limited recharge. Large vertical hydraulic gradients occur in the uplands where wells probably are completed in different permeable interflow zones. The similarity of water-level fluctuations and elevations in the deeper zones of the Columbia River basalt unit beneath upland areas and those in the basalt unit in the basin suggests a direct connection between deep interflow zones in the uplands and the flow system beneath the valley floor.

This study provides an improved understanding and a framework of the regional hydrogeology of the Willamette Basin. The framework provides a basis and context for conducting more detailed studies. Based on the conceptual model of ground-water flow described in this report, regional and local ground-water models can test the concepts, simulate past and present ground-water flow, and predict the response of the hydrologic system to future pumping and recharge scenarios.

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Appendix A. Correlation of U.S. Geological Survey and Oregon Water Resources Department Identifiers for Selected Wells.

[Location is USGS station identifier and contains township, range, section, and letter code for quarter location in section]

Location	OWRD name	USGS name	Depth drilled, in feet below land surface
01N/02W-03AAD01	WASH 5090	453613122542901	305
01N/02W-03ABA	WASH 14	453618122544701	405
01N/02W-08BCA	WASH 5173	453514122575801	60
01N/02W-17ACC	WASH 5382	453417122572901	70
01N/02W-17DAB	WASH 5377	453414122571001	760
02N/03W-35CDD	WASH 5956	453628123012101	618
03N/01W-06BAA1	COLU 3379	454645122512201	92
01S/01E-24BBC01	MULT 63238	452827122382401	27
01S/01E-24BBC02	MULT 63239	452827122382402	98
01S/02E-13CDA1	None	452840122302202	17
01S/02E-13CDA2	None	452840122302201	54
01S/02E-16BAA01	MULT 63388	452921122340401	129
01S/02E-16BDA01	MULT 50871	452912122340401	437
01S/01W-17CBD	WASH 8862	452845122502301	414
01S/01W-21CDD2	WASH 8988	452751122485401	800
01S/01W-21DAD2	WASH 8976	452757122482001	395
01S/01W-21DDD	WASH 8986	452751122466001	145
01S/01W-33CBC	WASH 9205	452619122492401	325
01S/02W-23ACB	WASH 10143	452817122561501	805
02S/01E-20CBD1	CLAC 12346	452249122430801	238
02S/01E-20CBD2	CLAC 3165	452249122430901	40
02S/01E-21CCC	CLAC 3246	452234122415901	330
02S/02E-29DD	CLAC 4396	None	560
02S/04E-05CBB	CLAC 5535	452528122205501	205
02S/04E-29DAD	CLAC 6388	452033122195901	190
02S/01W-04ACC	WASH 11449	452534122485101	494
02S/01W-04BAD	WASH 11436	452551122485801	600
02S/01W-32ADD	WASH 51903	452113122493001	1,030
02S/02W-34ACD	WASH 3443	452118122545001	277
02S/02W-34ADB	WASH 13210	452119122544001	160
03S/01E-16DDD	CLAC 9327	451815122405401	202
03S/01E-17ACA	CLAC 9340	451845122423101	292
03S/01W-15CAC	CLAC 8184	451747122484801	920
03S/01W-24BAA01	CLAC 8491	451804122451201	620
03S/02W-36ABA	YAMH 2703	451626122522001	282

Appendix A. Correlation of U.S. Geological Survey and Oregon Water Resources Department Identifiers for Selected Wells—Continued.

[Location is USGS station identifier and contains township, range, section, and letter code for quarter location in section]

Location	OWRD name	USGS name	Depth drilled, in feet below land surface
03S/02W-36ACA	YAMH 2685	451611122522601	545
04S/01W-05CDC	MARI 308	451447122502101	120
04S/01W-06ADD	MARI 50403	451514122504401	365
04S/01W-11ADA01	MARI 53023	451429122455301	1,097
04S/01W-15BDD	CLAC 1952	451333122474901	245
04S/01W-19ACA01	MARI 56530	451237122510601	613
04S/01W-19ACD01	MARI 54896	451235122510401	350
04S/02W-01CDD01	None	451444122524701	12.6
04S/02W-01CDD02	None	451444122524601	3.9
04S/02W-02BBD	MARI 1044	451528122541301	166
05S/01W-28CCD01	None	450603122491601	2.83
05S/01W-28CCD02	None	450603122491602	17.7
05S/02W-01DDA	MARI 2218	450939122520901	200
05S/02W-08CBC01	MARI 18414	450856122580201	270
05S/02W-08CCA2	MARI 52504	450851122575801	106
05S/02W-08CCB1	MARI 52597	450851122580101	203
05S/02W-19DCC	MARI 2541	450758122590201	130
05S/03W-34CBB	YAMH 50041	450531123025901	57
05S/03W-36DAA	MARI 17239	450535122593201	109
06S/01W-06CCC	MARI 3054	450423122514701	165
06S/01W-08DAC01	MARI 55014	450341122493701	49
06S/01W-08DAC03	MARI 55016	450341122493702	35
06S/01W-08DAD01	MARI 53920	450340122493401	115
06S/01W-08DAD02	MARI 54951	450340122493403	53.6
06S/01W-08DAD03	MARI 54952	450340122493402	69.5
06S/01W-08DAD04	MARI 54953	450339122492801	55.1
06S/01W-08DAD05	MARI 55015	450339122492802	68.9
06S/01W-08DAD06	MARI 55017	450340122493404	45.2
06S/01W-09DCA	MARI 50456	450332122483801	850
06S/01W-15ABD01	MARI 3179	450313122472401	700
06S/01W-16AAB01	MARI 3197	450324122482801	830
06S/01W-16ABC01	MARI 51339	450312122484401	188
06S/01W-21CAD	MARI 3266	450200122485301	120
06S/01W-21CDC01	MARI 3280	450140122490701	323
06S/01W-21CDC02	MARI 51006	450141122490601	566
06S/01W-22AAA01	MARI 19510	450231122470401	630
06S/01W-36BBC	MARI 3653	450036122454101	176
06S/01W-36DBC1	MARI 3657	450013122450001	226

Appendix A. Correlation of U.S. Geological Survey and Oregon Water Resources Department Identifiers for Selected Wells—Continued.

[Location is USGS station identifier and contains township, range, section, and letter code for quarter location in section]

Location	OWRD name	USGS name	Depth drilled, in feet below land surface
06S/01W-36DDC	MARI 3652	445959122445001	526
06S/02W-06DAD	MARI 17263	450432122582001	120
06S/02W-17DAD	MARI 4160	450246122564801	136
06S/02W-17DBC	MARI 4092	450248122572601	315
06S/03W-04ACD	MARI 4816	450451123031901	70
06S/03W-06CBC	YAMH 1907	450435123063101	205
06S/04W-03ABD	YAMH 3189	450502123092501	382
07S/01W-02CAA01	MARI 5904	445923122462501	583
07S/02W-28ADD	MARI 7883	445606122554101	130
07S/02W-28ADD01	MARI 55258	445604122554501	304
07S/03W-18AB1	POLK 841	445808123055601	440
07S/03W-18BAD	POLK 1777	445803123060701	303
07S/03W-18BAD01	POLK 1781	445804123061201	323
08S/01W-30DDB1	MARI 8999	445032122505001	40
08S/01W-30DDB2	MARI 8971	445033122505101	160
08S/02W-12CDB01	MARI 9917	445306122524501	248
08S/02W-12CDB02	MARI 56786	445307122524701	425
08S/02W-13BAD01	MARI 10176	445244122523701	105
08S/03W-10DC	MARI 19624	None	332
08S/03W-11CCC	MARI 11727	445304123014101	270
08S/03W-35DDD	MARI 12984	444935123003701	264
09S/01W-14DCA	LINN 2705	444700122460701	326
09S/01W-15DCB01	LINN 50629	444704122473001	141
09S/01W-15DCB03	LINN 51763	444704122472801	406
11S/04W-28BDD1	LINN 4146	443512123105001	54
11S/04W-28CAA	LINN 14280	443500123105001	60
11S/04W-34CDA	LINN 8753	443358123093601	60
11S/04W-34DDC	LINN 8756	443352123090401	104
11S/05W-35DDD	LINN 10841	443349123150501	45
12S/02W-19CCB1	LINN 8054	443028122590901	47.5
12S/03W-07BCC2	LINN 50852	443234123063101	51
12S/03W-07CCB	LINN 50103	443211123062901	80
12S/03W-09BDC2	LINN 10510	443232123034501	80
12S/03W-12BAA	LINN 10391	443252122595301	65
12S/04W-01ABB	LINN 50097	443343123070501	65
12S/04W-35CDC	LINN 10817	442838123083001	115
12S/05W-02AAA	LINN 12120	443348123150201	260
15S/03W-19ACD1	LINN 14047	441508123053001	98

Appendix A. Correlation of U.S. Geological Survey and Oregon Water Resources Department Identifiers for Selected Wells—Continued.

[Location is USGS station identifier and contains township, range, section, and letter code for quarter location in section]

Location	OWRD name	USGS name	Depth drilled, in feet below land surface
16S/05W-26AAD	LANE 8725	440915123145601	30
17S/01W-29ACC	LANE 10127	440354122495501	43
17S/02W-30CAA1	LANE 10761	440341122584001	249
17S/02W-30CAA2	LANE 10762	440341122584002	50
17S/05W-02BAC1	LANE 12676	440736123154701	105
17S/05W-02BAC2	LANE 3203	440735123154601	25

Appendix B. Chlorofluorocarbon-Based Model Ages for Ground Water in the Willamette Basin, Oregon

By Stephen R. Hinkle

Introduction

Twenty-one wells were sampled for chlorofluorocarbons (CFCs) in October 1996 as part of the Willamette Ground-Water Project. Samples were analyzed for three CFCs: CCl_3F, CCl_2F_2, and $C_2Cl_3F_3$. Measurement of CFCs allows determination of CFC-model ages for ground water, where a CFC-model age is defined to be an estimate of the time-of-travel for water particles from their points of recharge at the water table to the open or screened interval of a well. CFC-dating techniques allow water recharged as far back as 1940 to be dated. CFC-dating theory, techniques and limitations are described in Busenberg and Plummer (1992), Busenberg and others (1998), and Plummer and Busenberg (2000).

Methods

Methods of CFC sample collection and analysis in this project were essentially identical to those used by Hinkle and Snyder (1997), with one important exception. Many wells chosen for sampling by Hinkle and Snyder (1997) had long open or screened intervals, and the resulting samples often probably represented mixtures of water of widely varying age. In contrast, in the present work, particular emphasis was placed on sampling wells with short open or screened intervals to minimize well-bore mixing of ground-water components. The resulting CFC-model ages are more meaningful than are CFC-model ages determined from wells with long open or screened intervals.

CFC-model ages are based upon CFC concentrations, temperature of water at the time of recharge, and the altitude of the water table at the time of recharge. The mean recharge temperature in the Portland Basin (which lies at the mouth of the Willamette Basin) was determined to be 8°C (degrees Celsius) (Hinkle and Snyder, 1997). Thus, the mean recharge temperature used in this study was assumed to be 8°C. A 2°C error in the estimate of recharge temperature would result in an error of 0 to 1 years for water recharged in the 1940s-1970s and 2 years for water recharged in the early to mid-1980s. The temperature dependence of CFC-model ages becomes more significant for water recharged since the late 1980s (errors of several years), but as will be seen later, none of the wells sampled in this project were open or screened close enough to the water table to yield such young water. Thus, uncertainty in recharge temperatures are not a significant source of error for these samples.

Recharge elevations were approximated by assuming that they were equal to the elevations of the static water levels in the wells. A 2,000-foot error in recharge elevation generally results in a difference of 0 to 1 year. Thus, although recharge elevations will be higher than elevations of static water levels in wells, the uncertainty associated with this approximation is negligible.

Degradation of CFCs will affect the CFC-based model ages. Degradation may occur in reducing environments. To evaluate redox conditions, dissolved oxygen and methane in ground-water samples were measured. Dissolved oxygen was measured electrometrically in a flow-through chamber in the field. Probes were calibrated daily and were periodically checked against anoxic solutions (deionized water with sodium sulfite added to chemically reduce oxygen). Dissolved methane was measured by gas chromatography (Busenberg and others, 1998).

Results

For each site, two to three samples were analyzed for CFCs. CFC concentrations, CFC-model recharge dates, dissolved-oxygen (DO) concentrations, selected physical data, and assigned CFC-model ages are presented in table B1. Figure B1 shows the CFC-model ages of water from the sampled wells.

Reducing conditions were widespread. DO concentrations at 16 sites were less than 0.3 mg/L (milligrams per liter), and even the site with the highest DO concentration (3.3 mg/L) cannot be assumed to represent only oxic water, as a sample with such a low DO concentration could represent a mixture of well-oxygenated and anoxic water. CFC dating in reducing environments requires consideration of redox conditions because microbial degradation of CFCs can occur in reducing environments. Degradation of CCl_3F is considerably faster (generally by at least an order of magnitude) than degradation of CCl_2F_2, and measurable degradation of CCl_2F_2 apparently does not occur until methanogenic conditions become well established (Plummer and Busenberg, 2000). Observed CCl_3F-model recharge dates generally are older than CCl_2F_2-model recharge dates (table B1), suggesting that some microbial degradation of CCl_3F

has occurred. Dissolved-methane concentrations were measured in samples from 10 of the 21 sites; all concentrations were <0.05 mg/L, indicating non-methanogenic or minimally methanogenic conditions. Thus, although CCl_3F-model recharge dates appear to be biased low (too old), CCl_2F_2-model recharge dates are reliable.

$C_2Cl_3F_3$ data are difficult to interpret in reducing environments. $C_2Cl_3F_3$, like CCl_3F, tends to undergo biodegradation in anoxic environments. Also, the abundant organic carbon that likely serves as an electron donor in these reducing environments also may serve to sorb $C_2Cl_3F_3$; $C_2Cl_3F_3$ sorbs to a much greater extent than do CCl_3F and CCl_2F_2 (Plummer and Busenberg, 2000). For these reasons, $C_2Cl_3F_3$-model recharge dates can be biased too old. $C_2Cl_3F_3$ is a liquid at common environmental temperature, whereas CCl_3F and CCl_2F_2 are gases; so in some respects, $C_2Cl_3F_3$ contamination can more easily occur than contamination by CCl_3F and CCl_2F_2. The result is that $C_2Cl_3F_3$-model recharge dates can be biased young due to contamination. Thus, for the data for this study area, CCl_2F_2-model recharge dates were considered more reliable than $C_2Cl_3F_3$-model recharge dates, and $C_2Cl_3F_3$-model recharge dates were not interpreted.

For 17 of the 21 sites sampled, the oldest CCl_2F_2-model recharge date for each site was used to assign the CFC-model age. The oldest CCl_2F_2-model recharge date was chosen to minimize potential influence of any minor contamination during sampling or analysis, and is consistent with the approach used by Hinkle and Snyder (1997). Assigned CFC-model ages ranged from 23 to >57 years.

Assignment of CFC-model ages for 3 of the 21 sites was complicated by the presence of contaminant-level concentrations of CFCs. For samples collected in 1996, a contaminant-level concentration of a CFC is defined to be a concentration greater than the concentration that would be in equilibrium with 1996 air. Contaminant-level concentrations result from introduction of CFCs to the aquifer by processes other than air-water equilibrium. Where contaminant-level concentrations of CFCs were detected in one or more samples for a given site, the water was considered to have been recharged earlier than the oldest apparent CCl_2F_2-model recharge date, but more recently than 57 years (limit of method for samples collected in late 1996). Thus, for each of the three sites with contaminant levels of CFCs, ranges of ages were assigned.

Assignment of a CFC-model age for the remaining site (well 06S/04W-03ABD) was less straightforward than it was for the other sites. The oldest CCl_3F-model recharge date for site 06S/04W-03ABD was more recent than the oldest CCl_2F_2-model recharge date. This pattern was observed at only two other sites (wells 06S/01W-36DDC and 06S/02W-06DAD). Water from these two wells is estimated to be older than 57 years because ages from CCl_2F_2 and $C_2Cl_3F_3$ analysis indicate the water is old and does not contain those CFCs. (In the case of 06S/01W-36DDC and 06S/02W-06DAD, small concentrations (few pg/kg or less) of CCl_3F detected in samples of

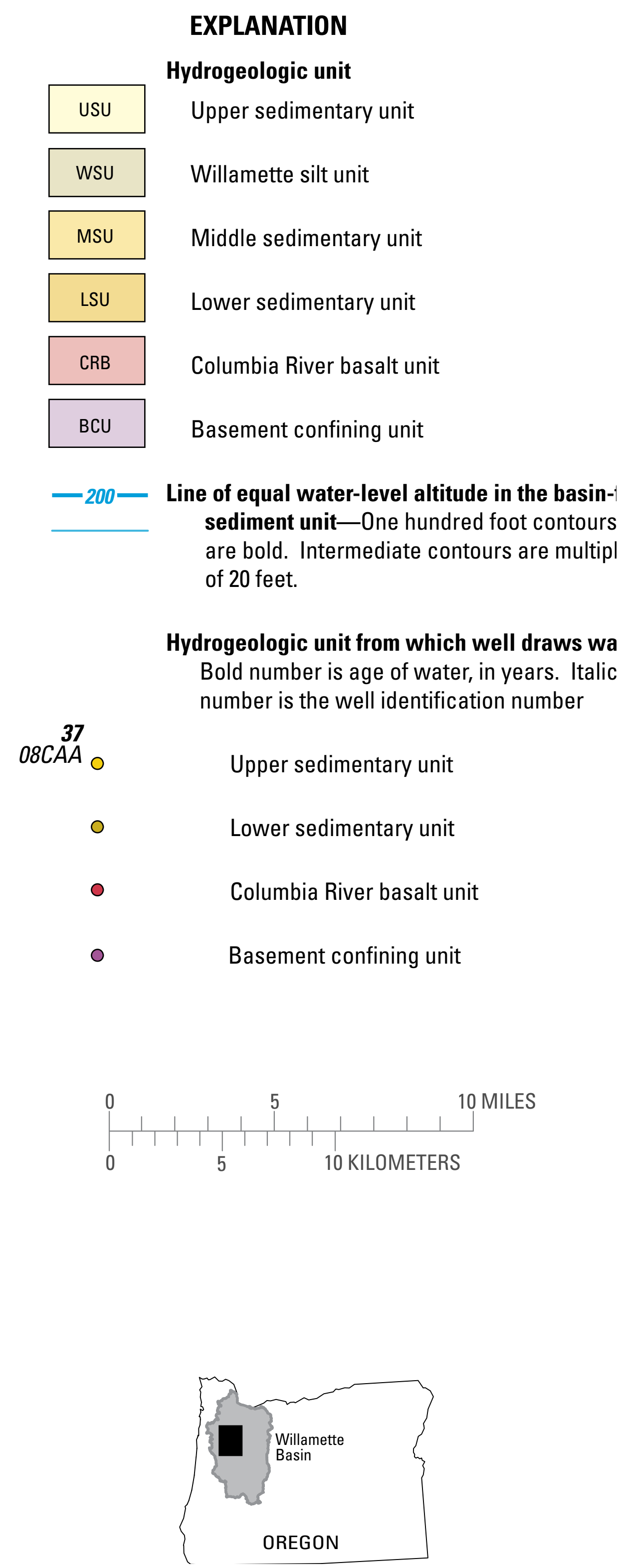
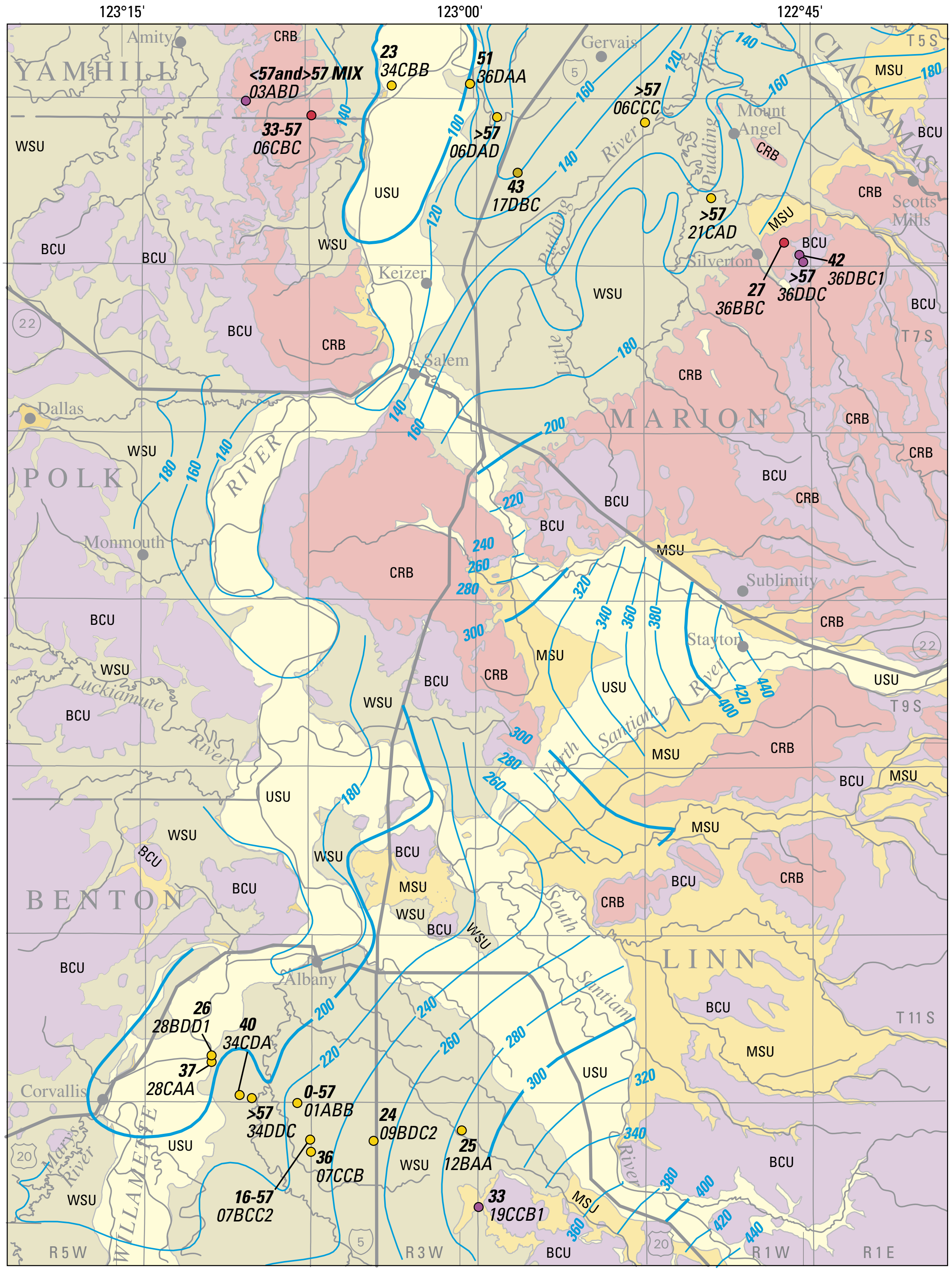


Figure B1. CFC-model ages for ground-water along two



See Table of Contents for mapping sources

transects and water-table contours in the basin-fill sediments, Willamette Basin, Oregon.

Table B1. Chlorofluorocarbon data for ground-water samples collected October 7–24, 1996

[Duplicate or triplicate samples were run for samples from each site. OWRD, Oregon Water Resources Department; ft NGVD 29, feet above NGVD 29; pg/kg, picograms per kilogram; mg/L, milligrams per liter; yrs, years; *, samples contain chlorofluorocarbon (CFC) concentrations greater than would be found in water at equilibrium with average global 1996 air; <, less than; >, greater than]

Location	OWRD name	USGS name	Sample date	Dis-solved oxygen (mg/L)	Recharge elevation[1] (ft NGVD 29)	CCl_3F concen-tration (pg/kg)	CCl_2F_2 concen-tration (pg/kg)	$C_2Cl_3F_3$ con-centra-tion (pg/kg)	CCl_3F model recharge date	CCl_2F_2 model recharge date	$C_2Cl_3F_3$ model recharge date	CFC model age of water (yrs)
05S/03W-34CBB	YAMH 50041	450531123025901	10/15/1996	1.8	90	235.6	146.7	36.0	1971.0	1974.0	1981.0	23
05S/03W-34CBB	YAMH 50041	450531123025901	10/15/1996		90	246.0	149.8	39.6	1971.5	1974.0	1981.5	
05S/03W-34CBB	YAMH 50041	450531123025901	10/15/1996		90	250.4	149.2	37.0	1971.5	1974.0	1981.0	
05S/03W-36DAA	MARI 17239	450535122593201	10/7/1996	<0.1	104	0.0	1.6	0.0	<1945.0	1946.0	<1954.5	51
05S/03W-36DAA	MARI 17239	450535122593201	10/7/1996		104	2.4	4.3	0.0	1950.5	1949.0	<1954.5	
06S/01W-06CCC	MARI 3054	450423122514701	10/8/1996	<0.1	128	2.0	0.4	0.0	1950.0	1941.5	<1954.5	>57
06S/01W-06CCC	MARI 3054	450423122514701	10/8/1996		128	0.0	0.0	0.0	<1945.0	<1940.0	<1954.5	
06S/01W-06CCC	MARI 3054	450423122514701	10/8/1996		128	0.6	0.0	0.0	1947.5	<1940.0	<1954.5	
06S/01W-21CAD	MARI 3266	450200122485301	10/8/1996	<0.1	142	0.0	0.0	0.0	<1945.0	<1940.0	<1954.5	>57
06S/01W-21CAD	MARI 3266	450200122485301	10/8/1996		142	0.0	0.0	0.0	<1945.0	<1940.0	<1954.5	
06S/01W-36BBC	MARI 3653	450036122454101	10/9/1996	0.1	210	34.2	100.5	4.3	1960.0	1970.5	1965.5	27
06S/01W-36BBC	MARI 3653	450036122454101	10/9/1996		210	18.3	95.2	0.0	1956.5	1970.0	<1954.5	
06S/01W-36BBC	MARI 3653	450036122454101	10/9/1996		210	17.5	88.4	6.9	1956.5	1969.5	1969.0	
06S/01W-36DBC1	MARI 3657	450013122450001	10/11/1996	<0.1	339	7.6	12.4	0.0	1953.5	1955.0	<1954.5	42
06S/01W-36DBC1	MARI 3657	450013122450001	10/11/1996		339	7.1	14.1	0.0	1953.0	1955.5	<1954.5	
06S/01W-36DBC1	MARI 3657	450013122450001	10/11/1996		339	6.0	14.2	0.0	1952.5	1955.5	<1954.5	
06S/01W-36DDC	MARI 3652	445959122445001	10/11/1996	<0.1	233	2.8	0.0	0.0	1950.5	<1940.0	<1954.5	>57
06S/01W-36DDC	MARI 3652	445959122445001	10/11/1996		233	3.4	4.3	0.0	1951.5	1949.0	<1954.5	
06S/01W-36DDC	MARI 3652	445959122445001	10/11/1996		233	2.4	0.0	0.0	1950.5	<1940.0	<1954.5	

Table B1. Chlorofluorocarbon data for ground-water samples collected October 7–24, 1996—Continued.

[Duplicate or triplicate samples were run for samples from each site. OWRD, Oregon Water Resources Department; ft NGVD 29, feet above NGVD 29; pg/kg, picograms per kilogram; mg/L, milligrams per liter; yrs, years; *, samples contain chlorofluorocarbon (CFC) concentrations greater than would be found in water at equilibrium with average global 1996 air; <, less than; >, greater than]

Location	OWRD name	USGS name	Sample date	Dissolved oxygen (mg/L)	Recharge elevation[1] (ft NGVD 29)	CCl_3F concentration (pg/kg)	CCl_2F_2 concentration (pg/kg)	$C_2Cl_3F_3$ concentration (pg/kg)	CCl_3F model recharge date	CCl_2F_2 model recharge date	$C_2Cl_3F_3$ model recharge date	CFC model age of water (yrs)
06S/02W-06DAD	MARI 17263	450432122582001	10/7/1996	<0.1	144	0.9	1.0	0.0	1948.5	1944.0	<1954.5	>57
06S/02W-06DAD	MARI 17263	450432122582001	10/7/1996		144	0.5	0.0	0.0	1947.0	<1940.0	<1954.5	
06S/02W-17DBC	MARI 4092	450248122572601	10/21/1996	<0.1	137	1.0	16.6	0.0	1948.5	1957.0	<1954.5	43
06S/02W-17DBC	MARI 4092	450248122572601	10/21/1996		137	0.9	10.6	0.0	1948.5	1954.0	<1954.5	
06S/02W-17DBC	MARI 4092	450248122572601	10/21/1996		137	1.1	16.8	0.0	1949.0	1957.0	<1954.5	
06S/03W-06CBC	YAMH 1907	450435123063101	10/15/1996	3.3	282	42.9	44.9	8.2	1961.0	1964.0	1970.0	33–57[2]
06S/03W-06CBC	YAMH 1907	450435123063101	10/15/1996		282	523.9	851.7	181.1	1979.0	*	*	
06S/03W-06CBC	YAMH 1907	450435123063101	10/15/1996		282	2825.4	305.8	84.7	*	1986.5	1988.0	
06S/04W-03ABD	YAMH 3189	450502123092501	10/10/1996	<0.1	739	5.6	5.8	0.0	1952.5	1950.5	<1954.5	<57&>57[3]
06S/04W-03ABD	YAMH 3189	450502123092501	10/10/1996		739	3.5	3.6	0.0	1951.5	1948.5	<1954.5	
06S/04W-03ABD	YAMH 3189	450502123092501	10/10/1996		739	3.2	3.1	0.0	1951.0	1948.0	<1954.5	
11S/04W-28BDD1	LINN 4146	443512123105001	10/24/1996	1.0	194	110.9	114.9	18.3	1966.5	1971.5	1976.0	26
11S/04W-28BDD1	LINN 4146	443512123105001	10/24/1996		194	96.3	106.1	11.1	1965.5	1971.0	1972.0	
11S/04W-28BDD1	LINN 4146	443512123105001	10/24/1996		194	98.6	106.8	12.7	1965.5	1971.0	1973.0	
11S/04W-28CAA	LINN 14280	443500123105001	10/17/1996	0.2	197	9.6	26.3	0.0	1954.0	1960.0	<1954.5	37
11S/04W-28CAA	LINN 14280	443500123105001	10/17/1996		197	9.1	27.2	0.0	1954.0	1960.5	<1954.5	
11S/04W-28CAA	LINN 14280	443500123105001	10/17/1996		197	9.8	28.2	0.0	1954.0	1960.5	<1954.5	
11S/04W-34CDA	LINN 8753	443358123093601	10/16/1996	<0.1	215	1.3	17.0	0.0	1949.0	1957.0	<1954.5	40
11S/04W-34CDA	LINN 8753	443358123093601	10/16/1996		215	1.4	17.5	0.0	1949.5	1957.0	<1954.5	
11S/04W-34CDA	LINN 8753	443358123093601	10/16/1996		215	0.0	16.6	0.0	<1945.0	1957.0	<1954.5	
11S/04W-34DDC	LINN 8756	443352123090401	10/17/1996	<0.1	209	0.0	0.0	0.0	<1945.0	<1940.0	<1954.5	>57
11S/04W-34DDC	LINN 8756	443352123090401	10/17/1996		209	0.0	0.0	0.0	<1945.0	<1940.0	<1954.5	
11S/04W-34DDC	LINN 8756	443352123090401	10/17/1996		209	0.0	0.0	0.0	<1945.0	<1940.0	<1954.5	

Table B1. Chlorofluorocarbon data for ground-water samples collected October 7–24, 1996—Continued.

[Duplicate or triplicate samples were run for samples from each site. OWRD, Oregon Water Resources Department; ft NGVD 29, feet above NGVD 29; pg/kg, picograms per kilogram; mg/L, milligrams per liter; yrs, years; * samples contain chlorofluorocarbon (CFC) concentrations great than would be found in water at equilibrium with average global 1996 air; <, less than; >, greater than]

Location	OWRD name	USGS name	Sample date	Dis-solved oxygen (mg/L)	Recharge elevation[1] (ft NGVD 29)	CCl_3F concen-tration (pg/kg)	CCl_2F_2 concen-tration (pg/kg)	$C_2Cl_3F_3$ con centra-tion (pg/kg)	CCl_3F model recharge date	CCl_2F_2 model recharge date	$C_2Cl_3F_3$ model recharge date	CFC model age of water (yrs)
12S/02W-19CCB1	LINN 8054	443028122590901	10/23/1996	<0.1	315	3.1	44.0	0.0	1951.0	1964.0	<1954.5	33
12S/02W-19CCB1	LINN 8054	443028122590901	10/23/1996		315	7.2	42.5	0.0	1953.5	1964.0	<1954.5	
12S/02W-19CCB1	LINN 8054	443028122590901	10/23/1996		315	5.1	47.6	0.0	1952.5	1964.5	<1954.5	
12S/03W-07BCC2	LINN 50852	443234123063101	10/22/1996	<0.1	231	0.0	231.5	0.0	<1945.0	1981.0	<1954.5	16–57[2]
12S/03W-07BCC2	LINN 50852	443234123063101	10/22/1996		231	1.0	352.9	0.0	1948.5	1990.0	<1954.5	
12S/03W-07BCC2	LINN 50852	443234123063101	10/22/1996		231	8.1	456.1	0.0	1953.5	*	<1954.5	
12S/03W-07CCB	LINN 50103	443211123062901	10/22/1996	<0.1	231	9.9	41.3	0.0	1954.0	1963.5	<1954.5	36
12S/03W-07CCB	LINN 50103	443211123062901	10/22/1996		231	15.4	37.2	0.0	1956.0	1963.0	<1954.5	
12S/03W-07CCB	LINN 50103	443211123062901	10/22/1996		231	6.5	29.4	0.0	1953.0	1961.0	<1954.5	
12S/03W-09BDC2	LINN 10510	443232123034501	10/23/1996	<0.1	250	6.0	127.6	0.0	1952.5	1972.5	<1954.5	24
12S/03W-09BDC2	LINN 10510	443232123034501	10/23/1996		250	6.1	129.0	0.0	1953.0	1972.5	<1954.5	
12S/03W-09BDC2	LINN 10510	443232123034501	10/23/1996		250	5.9	133.0	0.0	1952.5	1973.0	<1954.5	
12S/03W-12BAA	LINN 10391	443252122595301	10/17/1996	2.7	271	169.2	124.6	115.6	1969.0	1972.5	1993.5	25
12S/03W-12BAA	LINN 10391	443252122595301	10/17/1996		271	177.4	131.9	126.7	1969.5	1973.0	*	
12S/03W-12BAA	LINN 10391	443252122595301	10/17/1996		271	173.3	119.8	121.3	1969.0	1972.0	*	
12S/04W-01ABB	LINN 50097	443343123070501	10/23/1996	2.8	223	5616.5	870.6	14.7	*	*	1974.0	0–57[2]
12S/04W-01ABB	LINN 50097	443343123070501	10/23/1996		223	5546.9	842.4	9.3	*	*	1971.0	

[1]Recharge elevation, assumed equal to elevation of static water level above NGVD29 in feet.

[2]Range of age for water given because sample contaminated with CFC by process other than air-water equilibrium.

[3]Mixture of water, one part < 57 yrs old and one part > 57 yrs old.

apparently old water lead to more recent CCl_3F-model recharge dates than CCl_2F_2-model recharge dates. Synthetic components in water pumps have been shown to be a source of CCl_3F contamination to water samples (Plummer and Busenberg, 2000), and may have been the source of the observed small amounts of CCl_3F in these two water samples.) In the case of site 06S/04W-03ABD, mixing of water from different contributing zones in the aquifer is the most likely explanation for the differences between CCl_3F and CCl_2F_2-model recharge dates. The atmospheric ratio of CCl_3F to CCl_2F_2 increased steadily between the late 1940s and late 1970s (Plummer and Busenberg, 2000). A mixture of CFC-free (pre-1940) water with CFC-containing (post-1940) water frequently results in different CCl_3F- and CCl_2F_2-model recharge dates, with CCl_3F-model recharge dates being more recent than CCl_2F_2-model recharge dates (Plummer and Busenberg, 2000). This was observed with site 06S/04W- 03ABD (CCl_3F-model recharge date of 1951 and CCl_2F_2-model recharge date of 1948). If no processes other than air-water equilibrium and mixing have affected CFC concentrations in the water at this site, the ratios of CCl_3F to CCl_2F_2 could be interpreted as being a mixture of 22 percent water recharge in 1955 with 78 percent water recharged prior to 1940. These calculations would not be valid for conditions where both mixing of water and significant biodegradation of CCl_3F occurred. In the presence of significant biodegradation, it would be safest to simply state that the water from this site contains a mixture of pre- and post-1940 water. It is worth noting that the contributing interval of this site (77 feet) was longer than at any of the other 20 sites, and, unlike any of the other sites, this site contained three distinct contributing zones. These well-construction data are consistent with the interpretation of a mixture of water at this site.

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Appendix C. Seepage Estimates of Selected Streams using Streamflow Measurements, Willamette Basin, Oregon

[Data source refers to source of seepage measurements; ft³/s, cubic feet per second; RM, river mile; MF, Middle Fork; bold numbers indicate seepage exceeds measurement uncertainty]

Stream name	Reach	Date	Estimated gain (+) or loss (-) (ft³/s)	Gain/loss as % of streamflow	Cumulative gain/loss (ft³/s)	Cumulative gain/loss as % of streamflow	Data source
Butte Creek	RM 10.3-5.9	6/30/99	**-9.1**	-19%			
	RM 5.9-1.0	6/30/99	**8.2**	15%	-0.9	-2%	This study
	RM 10.3-5.9	9/16/99	**-2**	-52%			
	RM 5.9-1.0	9/16/99	**-2.2**	-132%	**4.2**	-253%	This study
	RM 10.3-5.9	5/30/00	0	0%			
	RM 5.9-1.0	5/30/00	2	2%	2	2%	This study
	RM 10.3-5.9	9/12/00	**-1.8**	-17%			
	RM 5.9-1.0	9/12/00	**2.2**	17%	0.4	3%	This study
Drift Creek	RM 6.5-3.2	6/23/99	**2.09**	22%			
	RM 3.2-0.6	6/23/99	-0.17	-2%	**1.9**	20%	This study
	RM 6.5-3.2	9/15/99	**0.07**	11%			
	RM 3.2-0.6	9/15/99	-0.05	-8%	0.02	3%	This study
	RM 6.5-3.2	6/2/00	**2.34**	13%			
	RM 3.2-0.6	6/2/00	**1.97**	10%	**4.31**	21%	This study
	RM 6.5-3.2	9/11/00	**-0.18**	-11%			
	RM 3.2-0.6	9/11/00	0.01	1%	**-0.17**	-10%	This study
Abiqua Creek	RM 5.8-2.4	6/1/00	9	6%			
	RM 2.4-0.4	6/1/00	-1	-1%	8	6%	This study
	RM 5.8-2.4	9/13/00	**-3.8**	-37%			
	RM 2.4-0.4	9/13/00	**1.2**	10%	**-2.6**	-23%	This study

Appendix C. Seepage Estimates of Selected Streams using Streamflow Measurements, Willamette Basin, Oregon—Continued

[Data source refers to source of seepage measurements; ft^3/s, cubic feet per second; RM, river mile; MF, Middle Fork; bold numbers indicate seepage exceeds measurement uncertainty]

Stream name	Reach	Date	Estimated gain (+) or loss (-) (ft^3/s)	Gain/loss as % of streamflow	Cumulative gain/loss (ft^3/s)	Cumulative gain/loss as % of streamflow	Data source
Pudding River	RM 49.7-45.5	5/2/96	5	1%			
	RM 45.5-40.7	5/2/96	26	3%	31	4%	Lee and Risley, 2002
	RM 26.8-22.3	5/3/96	38	4%	38	4%	Lee and Risley, 2002
	RM 22.3-17.5	5/3/96	44	4%	82	7%	Lee and Risley, 2002
	RM 17.5-8.1	5/3/96	75	5%	**157**	11%	Lee and Risley, 2002
	RM 49.7-45.5	9/24/96	-2.6	-5%			Lee and Risley, 2002
	RM 45.5-40.7	9/24/96	**-5.8**	-12%	**-8.4**	-18%	Lee and Risley, 2002
	RM 26.8-22.3	9/25/96	**32.6**	29%	**32.6**	29%	Lee and Risley, 2002
	RM 22.3-17.5	9/25/96	**-23.2**	-22%	9.4	9%	Lee and Risley, 2002
	RM 17.5-8.1	9/25/96	11.8	9%	**21.2**	16%	Lee and Risley, 2002
	RM 49.7-45.5	9/16-17/1999	0.83	3%	0.83	3%	This study
	RM 45.5-40.7	9/20/99					
	RM 40.7-26.8	9/20/99	**4.7**	17%	**4.7**	17%	This study
	RM 26.8-23.4	9/20-21/1999	0	0%	**4.7**	17%	This study
	RM 23.4-17.5	9/21/99	**3.87**	11%	**8.57**	25%	This study
	RM 17.5-8.1	9/21-22/1999	**5.03**	12%	**13.6**	33%	This study
	RM 8.1-5.1	9/22/99	1.22	3%	**14.82**	31%	This study
	RM 49.7-45.5	9/16-17/2000	-0.7	-3%			This study
	RM 45.5-40.7	9/20/00	0.1	0%	-0.6	-3%	This study
	RM 40.7-23.4	9/20/00	0.8	2%	0.2	1%	This study
	RM 23.4-17.5	9/21/00	-1.3	-3%	-1.1	-3%	This study
	RM 17.5-8.1	9/21-22/2000	**8.3**	16%	7.2	14%	This study
	RM 8.1-5.1	9/22/00	1.1	2%	8.3	14%	This study

Appendix C. Seepage Estimates of Selected Streams using Streamflow Measurements, Willamette Basin, Oregon—Continued

[Data source refers to source of seepage measurements; ft³/s, cubic feet per second; RM, river mile; MF, Middle Fork; bold numbers indicate seepage exceeds measurement uncertainty]]

Stream name	Reach	Date	Estimated gain (+) or loss (-) (ft³/s)	Gain/loss as % of streamflow	Cumulative gain/loss (ft³/s)	Cumulative gain/loss as % of streamflow	Data source
South Yamhill	RM 37.7-26.9	06/12-13/96	10.3	0%	10.3	0%	Lee and Risley, 2002
	RM 26.9-16.7	06/12-13/96	38.7	4%	49	4%	Lee and Risley, 2002
	RM 16.8-5.6	06/12-13/96	**95.1**	10%	**144.1**	13%	Lee and Risley, 2002
	RM 37.7-26.9	9/18/96	8	5%	8	5%	Lee and Risley, 2002
South Santiam	RM 37.0-33.4	4/30/96	374.2	9%			Lee and Risley, 2002
	RM 33.5-27.7	5/1/96	-160.7	-4%	213.5	5%	Lee and Risley, 2002
	RM 27.7-23.3	5/2/96	-150.7	-4%	62.8	1%	Lee and Risley, 2002
	RM 23.3-18.2	5/3/96	-427.6	-11%	-364.8	-10%	Lee and Risley, 2002
	RM 37.0-33.4	9/17/96	29	4%	29		Lee and Risley, 2002
	RM 33.5-27.7	9/18/96	-77.8	-11%	-48.8	-7%	Lee and Risley, 2002
	RM 27.7-23.3	9/19/96	62.7	8%	13.9	2%	Lee and Risley, 2002
	RM 23.3-18.2	9/20/96	-47.7	-7%	-33.8	-5%	Lee and Risley, 2002
MF Willamette River	RM 195-192.8	4/15/96	-4.7	-0%	-4.7	-0%	Lee and Risley, 2002
	RM 192.8-190.2	4/15/96	-103.4	-5%	-108.1	-6%	Lee and Risley, 2002
Willamette River	RM 169.6-163.7	5/7/96	117	2%	117	2%	Lee and Risley, 2002
	RM 163.7-161.0	5/8/96	190	3%	307	4%	Lee and Risley, 2002
	RM 161.0-156.3	5/9/96	-70	-1%	237	3%	Lee and Risley, 2002
	RM 156.3-149.6	5/10/96	-50	-1%	187	3%	Lee and Risley, 2002
	RM 134.4-127.5	5/8/96	-307.4	-4%	-307.4	-4%	Lee and Risley, 2002
	RM 127.5-124.4	5/8/96	60	1%	-247.4	-3%	Lee and Risley, 2002
	RM 124.4-119.9	5/8/96	110	1%	-137.4	-2%	Lee and Risley, 2002

Appendix C. Seepage Estimates of Selected Streams using Streamflow Measurements, Willamette Basin, Oregon—Continued

[Data source refers to source of seepage measurements; ft^3/s, cubic feet per second; RM, river mile; MF, Middle Fork; bold numbers indicate seepage exceeds measurement uncertainty]

Stream name	Reach	Date	Estimated gain (+) or loss (-) (ft^3/s)	Gain/loss as % of streamflow	Cumulative gain/loss (ft^3/s)	Cumulative gain/loss as % of streamflow	Data source
Willamette River	RM 94.2-89.1	5/9/96	0	0%	0	0%	Lee and Risley, 2002
	RM 89.1-84.1	5/9/96	321.3	2%	321.3	2%	Lee and Risley, 2002
	RM 84.1-77.8	5/9/96	136.6	1%	457.9	3%	Lee and Risley, 2002
	RM 52.4-46.5	5/10/96	64.1	0%	64.1	0%	Lee and Risley, 2002
	RM 46.5-43.0	5/10/96	-224	-1%	-159.9	-1%	Lee and Risley, 2002
	RM 43.0-39.0	5/10/96	593	4%	433.1	3%	Lee and Risley, 2002
MF Willamette River	RM 195-192.8	7/23/96	**-350**	-14%	-350	-14%	Lee and Risley, 2002
	RM 192.8-190.5	7/23/96	**381.4**	14%	31.4	1%	Lee and Risley, 2002
	RM 190.5-187.8	7/23/96	-95.9	-4%	-64.5	-2%	Lee and Risley, 2002
Willamette River	RM 169.6-163.3	7/24/96	370.8	7%	370.8	7%	Lee and Risley, 2002
	RM 163.7-161.0	7/24/96	-50	-1%	320.8	6%	Lee and Risley, 2002
	RM 161.0-156.3	7/24/96	180	3%	500.8	10%	Lee and Risley, 2002
	RM 156.3-149.6	7/24/96	-30	-1%	**470.8**	9%	Lee and Risley, 2002
	RM 134.4-127.5	7/30/96	-191.7	-4%	-191.7	-4%	Lee and Risley, 2002
	RM 127.5-124.4	7/30/96	-49.1	-1%	-240.8	-5%	Lee and Risley, 2002
	RM 124.4-119.9	7/30/96	42.2	1%	-198.6	-4%	Lee and Risley, 2002
	RM 94.2-89.1	7/31/96	11.7	0%	11.7	0%	Lee and Risley, 2002
	RM 89.1-84.1	7/31/96	-31.3	-0%	-19.6	-0%	Lee and Risley, 2002
	RM 84.1-77.8	7/31/96	-281.8	-4%	-301.4	-4%	Lee and Risley, 2002
	RM 52.4-46.5	8/1/96	-280.5	-4%	-280.5	-4%	Lee and Risley, 2002
	RM 46.5-43.0	8/1/96	-22.7	-0%	-303.2	-4%	Lee and Risley, 2002
	RM 43.0-39.0	8/1/96	219.3	3%	-83.9	-1%	Lee and Risley, 2002

Appendix C. Seepage Estimates of Selected Streams using Streamflow Measurements, Willamette Basin, Oregon—Continued

[Data source refers to source of seepage measurements; ft^3/s, cubic feet per second; RM, river mile; MF, Middle Fork; bold numbers indicate seepage exceeds measurement uncertainty]

Stream name	Reach	Date	Estimated gain (+) or loss (-) (ft^3/s)	Gain/loss as % of streamflow	Cumulative gain/loss (ft^3/s)	Cumulative gain/loss as % of streamflow	Data source
Tualatin River	RM 58.8-51.4	low flow	**13.4**	12%	13.4	12%	Kelly and others, 1999
	RM 51.5-38.4	low flow	7.2	5%	20.6	14%	Kelly and others, 1999
	RM 38.4-33.3	low flow	15.1	8%	35.7	18%	Kelly and others, 1999
	RM 33.3-1.8	low flow	9.5	5%	45.2	24%	Kelly and others, 1999

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